JOINT TRANSPORTATION RESEARCH PROGRAM

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Investigation of Low Friction on Asphalt Pavements

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16. Abstract

This study explores low-friction issues in specific asphalt pavements utilizing dolomite aggregates within an Indiana Department of Transportation district. It examines the frictional characteristics of these aggregates, concentrating on initial friction (PSV0) and long-term friction retention (PSV10). Employing a mix of laboratory tests, field data analysis, and statistical modeling, the research assesses how mechanical, physical, and chemical properties influence the overall friction behavior of dolomite aggregates.

The evaluation of Design Mix Formulas (DMFs) revealed no statistically significant effect on pavement friction, with variations more closely tied to aggregate quality and construction practices rather than the mix design itself. Inconsistent friction results were observed in projects using the same DMF, underscoring the importance of aggregate quality. The transition from Superpave4 to Superpave5 showed no correlation with friction outcomes. Chemical property analyses highlighted magnesium (Mg) content as critical in determining initial and retained friction performance, identifying an optimal Mg range of 11.35%-12.63% (MgO: 18.82%-20.94%) for a balance between initial friction and long-term durability. Field samples were compared with laboratory results, indicating that low PSV0, rather than excessive wear, primarily contributed to low friction in certain road sections. Additionally, a moderate correlation (0.51) between friction loss (ΔPSV) and average annual daily traffic (AADT) suggests that high-traffic roads are more prone to polishing effects. The study also assessed the role of secondary aggregates, such as steel slag, in improving friction retention, proposing that blended aggregates may enhance long-term performance.

Recommendations include optimal Mg content thresholds, effective aggregate selection strategies, and enhanced quality control and assurance measures during construction. Emphasizing the need for adequate aggregate angularity and the inclusion of steel slag, these findings provide a foundation for future research and policy development aimed at improving long-term pavement friction performance.

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EXECUTIVE SUMMARY

Introduction

The friction performance of pavement surfaces plays a critical role in roadway safety, influencing vehicle handling, braking efficiency, and overall driving conditions. This study investigates the friction characteristics of dolomite aggregates used in Hot Mix Asphalt (HMA) mixtures, with a particular focus on macrotexture, microtexture, and frictional durability. By analyzing laboratory and field-collected samples, this study identifies the key factors influencing initial friction (PSV0) and long-term friction retention (PSV10), aiming to optimize dolomite selection and pavement design strategies. This study provides a data-driven framework for optimizing dolomite selection and mixture design to enhance pavement friction performance. By establishing a scientifically grounded magnesium oxide (MgO) threshold, this research helps guide material selection, improving road safety and durability.

Methodology

The study employed a multifaceted research approach, integrating laboratory testing, field data collection, advanced texture analysis, and statistical modeling. Laboratory evaluations included mechanical durability assessments such as Los Angeles Abrasion (LAA) and Micro-Deval Abrasion (MDA) tests, while chemical composition was analyzed through x-ray fluorescence (XRF) techniques. Field testing measured friction and texture properties across various roadway sections, comparing results from different dolomite sources and mix designs. Additionally, hierarchical clustering and decision tree modeling were applied to determine optimal material thresholds, particularly magnesium content, to balance PSV0 and PSV10.

By combining laboratory findings with real-world performance data, this study provided a science-based framework for optimizing dolomite aggregate selection in HMA pavements. The insights gained from this research contribute to a deeper understanding of aggregate friction performance and offer practical recommendations for improving pavement material specifications to enhance roadway safety and durability. To assess the performance of dolomite aggregates, a comprehensive experimental and analytical framework was implemented:

- Field Selection and Data Collection
  - Fourteen road sections were selected for investigation based on the friction number (FN) at a standardized test speed (40 mph), or FN40, data and construction records.
  - Core samples were extracted and tested for friction and texture properties using Circular Track Meter (CTM), Dynamic Friction Tester (DFT), and Laser Texture Scanner (LTS).
- Laboratory Testing and Analysis
  - A Polished Stone Value (PSV) test was conducted using a British Pendulum Tester (BPT) to evaluate initial and postpolishing friction.
  - Mechanical and physical properties, including MDA, LAA, Bulk Specific Gravity (BSG), Water Absorption (WA), and Soundness, were measured.
  - Chemical composition analysis using XRF was performed to examine correlations between magnesium oxide, calcium oxide (CaO), and silicon dioxide (SiO_2) content versus friction performance.
- Clustering and Decision Tree Analysis
  - Hierarchical clustering and decision tree models were developed to classify dolomite sources based on magnesium content and frictional stability (ΔPSV).
  - Optimal magnesium oxide thresholds were determined to ensure a balance between initial friction and long-term durability.

Key Findings

1. Initial Friction and Dolomite Composition
   - Low initial aggregate friction (PSV0) may be due to a higher magnesium (Mg) content (> 12.63%).
   - Findings from the clustering algorithm and decision tree model indicate that dolomite sources with moderate magnesium content (11.35–12.63%) provide both sufficient initial friction and long-term durability.
   - Aggregates with higher titanium dioxide (TiO_2) and aluminum oxide (Al_2O_3) tend to exhibit higher PSV0.
2. Long-Term Friction Performance and Abrasion Resistance
   - Higher magnesium content (>11.35%) demonstrates improved abrasion resistance and reduced friction loss over time.
   - Dolomites with lower magnesium content (<11.35%) show higher initial friction but greater friction loss (ΔPSV).
   - ΔPSV is moderately correlated (0.51) with traffic load (Annual Average Daily Traffic [AADT]), indicating that high-traffic roadways are more susceptible to polishing effects.
3. Field Versus Laboratory Performance
   - Field-collected aggregates exhibited PSV10 values compared comparable to or higher than laboratory-tested samples, due probably to the contribution of other types of aggregate in the mixture.
   - The newly constructed pavement sections with low friction also exhibited insufficient initial friction (PSV0).
   - The presence of secondary aggregate (e.g., steel slag) might enhance friction retention in mixtures.
4. Design Mix Formulas (DMFs) and Friction
   - The evaluation of DMFs revealed no statistically significant effect on pavement friction, with variations more closely tied to aggregate quality and construction practices rather than the mix design itself.
   - Inconsistent friction results were observed in projects using the same DMF, underscoring the importance of aggregate quality. The transition from Superpave4 to Superpave5 showed no correlation with friction outcomes.

Recommendations

Based on the findings, the following recommendations are proposed:

- The vast majority of dolomite samples from different sources contained more than 10.3% magnesium, indicating that the current Indiana Department of Transportation (INDOT) minimum magnesium content of 10.3% for dolomite is well justified.
- The friction properties of dolomite aggregate vary with their magnesium content. The test results suggest that dolomite aggregates with magnesium content of 11.35–12.63% (magnesium oxide: 18.82–20.94%) can minimize early-stage friction deficiencies while maintaining long-term durability.
- To enhance the early-stage friction performance of pavements using dolomite aggregates, it is necessary to ensure necessary aggregate angularity and sufficient crushed particles. It is also shown that blending dolomite aggregate with steel slag is an effective approach to enhance friction performance.
- Macrotexture and microtexture parameters should be jointly considered when evaluating pavement friction.
- Close-range photogrammetric methods could enhance texture analysis accuracy, particularly for assessing PSV test specimens in laboratory settings.
- The use of International Friction Index (IFI) parameters (F60 and S_p) in pavement friction assessments should be expanded, as they demonstrated strong correlations between field and laboratory results.
- Develop guidelines for the inclusion of secondary aggregates (e.g., steel slags and calcined bauxite) to improve abrasion resistance and enhance long-term friction.

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1. INTRODUCTION

1.1 Research Background and Objectives

The Crawfordsville District of the Indiana Department of Transportation (INDOT) has recently identified concerns regarding low friction on several newly resurfaced road sections. Routine friction testing, conducted at both network and project levels, revealed that multiple roadway segments exhibited significant friction loss within 2–3 years of resurfacing, raising safety concerns.

INDOT's Research Division oversees friction testing across the roadway network, with interstates evaluated annually and other roads tested on a three-year cycle. When sections exhibited potentially low friction, project-level testing was conducted for further validation. Among the first six identified locations, only one segment met acceptable friction standards, while the remaining sections required urgent corrective measures.

To investigate the issue, INDOT's Materials and Tests Division, Research Division, and Crawfordsville District collaborated to examine possible causes. A review of pavement design mix formulas (DMFs) indicated that most affected roads utilized dolomitic #11 crushed stone. Laboratory analysis of this source confirmed that its Micro-Deval Abrasion (MDA) loss and magnesium (Mg) content fell within acceptable limits, and macrotexture evaluations from select sections suggested adequate surface texture. However, the analysis of hot mix asphalt (HMA) design specifications did not provide conclusive explanations for the observed friction deficiencies.

Since the initial discovery, six additional road segments have been flagged through network-level friction testing, bringing the total to 12 affected locations. With the likelihood of further cases emerging, a comprehensive study was launched to determine the underlying causes of low pavement friction and develop effective solutions.

Adequate friction is essential for roadway safety, influencing vehicle braking distances and driving stability. Given the unexpected friction loss observed in resurfaced roadways, this study aimed to systematically evaluate the role of dolomite aggregate properties in pavement friction performance.

The primary objectives of this research include:

1. Identify the primary causes of low friction in newly resurfaced roadways.
2. Evaluate the role of dolomite aggregate properties (physical, mechanical, and chemical) in friction performance.
3. Determine optimal material thresholds, particularly magnesium content, to balance initial friction (PSV0) and long-term durability (PSV10).
4. Analyze traffic-induced polishing effects (ΔPSV) to assess how friction retention changes over time.
5. Develop practical recommendations for improving pavement design and aggregate selection to enhance long-term friction.

To achieve these objectives, this study integrated laboratory testing, field data collection, texture analysis, and statistical modeling to develop science-based guidelines for optimizing dolomite selection in HMA pavement surfaces.

1.2 Literature Review

The friction performance of pavement surfaces depends on the mechanical, physical, and chemical properties of aggregates, which influence durability, polishing resistance, and macrotexture characteristics. Various studies have explored the frictional performance of different aggregate types, including dolomite, limestone, gravel, steel slag, and calcined bauxite.

1.2.1 Aggregate Types and Friction

Research indicates that gravel generally outperforms dolomite in friction retention, while limestone exhibits the lowest friction among common aggregates (Bao et al., 2024). Steel slag has been found to maintain superior friction compared to natural aggregates across different polishing stages (Uz & Gökalp, 2017; Zong et al., 2021). Calcined bauxite, known for its exceptional durability, significantly enhances surface resistance when incorporated into asphalt mixtures at rates between 25–50% (Xiong et al., 2021). In contrast, high dolomite content (> 50%) accelerates surface deterioration, reducing long-term friction (Gu et al., 2022).

1.2.2 Mechanical Properties and Friction Performance

Abrasion resistance is a critical factor in aggregate durability. The Los Angeles Abrasion (LAA) test assesses fragmentation resistance, while the MDA test evaluates wear resistance under wet conditions. Studies have shown that aggregates with lower LAA and MDA values generally exhibit better friction retention (Ajalloeian & Kamani, 2019; Heitzman et al., 2015). However, some researchers argue that LAA does not fully replicate real-world wear conditions (Alexander & Mindess, 2005), making MDA a preferred metric for evaluating moisture-related degradation (Cuelho et al., 2008; Y. Wu et al., 1998).

The Polished Stone Value (PSV) test measures friction performance after polishing, offering insights into long-term friction. Studies indicate that macrotexture negatively correlates with PSV, whereas microtexture shows a positive correlation (Liu et al., 2020). Aggregates with high PSV values, combined with low LAA and MDA losses, typically provide better friction performance (Yu et al., 2019; Zhan et al., 2021).

1.2.3 Chemical Properties and Friction Performance

Chemical composition plays a significant role in aggregate performance. Research suggests that aluminum oxide (Al_2O_3) and titanium dioxide (TiO_2) enhance hardness, while calcium oxide (CaO) and magnesium oxide (MgO) tend to reduce hardness (Bao et al., 2024; Li et al., 2017; Li et al., 2021). The relationship between chemical composition and friction retention is complex, as high magnesium levels improve durability (resistance to changes in PSV, LAA, and MDA) but may increase susceptibility (Bao et al., 2024).

TABLE 1.1
Magnesium Content Requirements for Dolomite Defined by Different States.

State	Definition	Mg (%)	MgO (%)
IN (INDOT, 2024)	At least 10.3% elemental Mg	≥ 10.3[a]	≥ 17.1
OH (ODOT, 2016)	More than 50% $CaMg(CO_3)_2$ and less than 10% of $CaCO_3$	≥ 6.6	≥ 10.94
IL (IDOT, 2011)	At least 11.0% MgO	≥ 6.6	≥ 11.0
IA (Iowa Department of Transportation, 2018)	At least 15% MgO	≥ 9.0	≥ 15.0
KY (Kentucky Transportation Cabinet, n.d.)	At least 37% $MgCO_3$	≥ 10.7	≥ 17.8
NE (NDOT, 2017)[b]	$CaCO_3$: $MgCO_3$ = 4:3	≤ 11.2	≤ 18.5
NY (New York State Department of Transportation, 2022)[b]	Ca : Mg = 1:1	≤ 13.2	≤ 21.9

[a] The maximum content of Mg in dolomite is 13.2% (West, et al., 2001)
[b] If there are impurities in the aggregate, the Mg content may be less than the value (11.2 and 13.2)

Dolomite classification also varies across state transportation agencies. INDOT defines dolomite as containing at least 10.3% elemental magnesium (17.1% magnesium oxide), whereas other states, such as Ohio and Illinois, set lower thresholds (≥ 6.6%), and Iowa (≥ 9%) and Kentucky (≥ 10.7%) impose stricter limits (INDOT, 2024; Ohio Department of Transportation [ODOT], 2016; Illinois Department of Transportation [IDOT], 2011). Table 1.1 compares magnesium content requirements for dolomite across various states.

1.2.4 *Friction Measurement Techniques*

Pavement friction is commonly evaluated using instruments such as the British Pendulum Tester (BPT), Dynamic Friction Tester (DFT), and Locked-Wheel Skid Tester (LWST; American Association of State Highway and Transportation Officials [AASHTO], 2021; ASTM International [ASTM], 2015). The Three-Wheel Polishing Device has also gained popularity for simulating real-world pavement wear (Fowler & Rached, 2012; Heitzman & Erukulla, 2011). While these methods provide valuable friction performance data, their results are not directly interchangeable, requiring standardized interpretation guidelines.

The literature underscores the complex interplay between aggregate properties, mix design, and friction, highlighting the need for further research into dolomite's friction performance in asphalt pavements.

1.3 Research Scope and Key Tasks

This study aims to identify the causes of low friction in asphalt-overlaid roadways and develop guidelines for optimizing dolomite selection in pavement applications. The research encompasses DMF comparison, field investigations, laboratory testing, texture analysis, and statistical modeling. Key tasks include:

1.3.1 *Field Selection and Data Collection*

- Compared friction performance of pavement sections constructed using different DMFs that included #11 dolomite.
- Selected 14 road sections across the Crawfordsville District based on the friction number (FN) at a standardized test speed (40 mph), or FN40, friction data and pavement design specifications.
  - Conducted in-field friction and texture measurements using Circular Track Meter (CTM), DFT, and Laser Texture Scanner (LTS).
- Collected field cores from multiple pavement sections.

1.3.2 *Laboratory Testing and Analysis*

- Evaluated abrasion resistance using LAA, MDA, and PSV tests.
- Assessed physical properties (bulk specific gravity, water absorption, soundness, and hardness).
- Analyzed chemical composition using x-ray fluorescence (XRF).

1.3.3 *Texture Characterization and Friction Correlation*

- Developed a three-dimensional (3D) photogrammetric method for macrotexture and microtexture analysis.
- Identified key texture parameters influencing friction performance.
- Conducted correlation analyses between friction (PSV0, PSV10, ΔPSV) and aggregate properties.

1.3.4 *Clustering and Decision Tree Analysis*

- Applied hierarchical clustering and decision-tree modeling to determine magnesium oxide thresholds for optimal friction performance.
- Identified an optimal magnesium oxide range of 18.82–20.94% (Magnesium: 11.35–12.63%).

1.3.5 *Field Validation and Practical Implications*

- Extracted and tested aggregates from field-collected cores.
- Confirmed that low PSV0 values, rather than excessive polishing (ΔPSV), were the primary cause of early friction decline.
- Evaluated the role of secondary aggregates (e.g., steel slag) in improving friction retention.

1.3.6 *Recommendations and Future Research*

- Established magnesium oxide thresholds for optimized dolomite selection in pavement design.
- Suggested further real-world validation to refine findings and explore aggregate interaction effects.

This comprehensive investigation enhances the understanding of dolomite's role in friction and informs practical recommendations for improving roadway safety and durability.

2. FIELD AND LABORATORY EVALUATION OF PAVEMENT MIXTURE FRICTION AND SURFACE TEXTURE PROPERTIES

2.1 Problem Statement

Adequate friction between vehicle tires and pavement surfaces, particularly under wet conditions, is critical for reducing skid-related crashes. Numerous studies have established a correlation between low pavement wet friction and increased skidding accident rates (Hall et al., 2009; Kamel & Gartshore, 1982). While other pavement-tire interaction concerns (e.g., noise) also warrant attention, Federal and state transportation agencies must prioritize maintaining sufficient friction levels throughout the service life of pavement to ensure public safety.

Pavement friction performance is governed by the interaction between vertical tire load and the horizontal forces generated at the pavement-tire interface. The LWST is the most widely used device for in-situ measurement of pavement wet friction at the network level in the United States. According to ASTM E274 (ASTM, 2020b), the LWST assesses friction by calculating FN40. In Indiana, routine network-level friction testing is conducted on all highways every 1–3 years. Recent tests in the Crawfordsville District have revealed low friction values on multiple roadway sections, many of which were constructed within 5 years of construction, prompting an urgent need for friction restoration.

An analysis of the HMA DMFs used on these problematic roadways revealed a common factor: dolomitic #11 crushed stone was used in most of these sections. Research indicates that the polish resistance of dolomite aggregates improves with higher magnesium content (Bao et al., 2024). This raises concerns about the relationship between HMA surface course design specifications and premature friction loss. Therefore, this study aims to investigate the underlying causes of low pavement friction and evaluate the impact of HMA mixture designs on surface friction characteristics.

Among the four primary factors influencing pavement friction—pavement material and surface texture properties, vehicle operating characteristics, tire properties, and environmental conditions—surface macrotexture and microtexture are the most critical for determining friction performance at different speeds:

- Macrotexture is particularly important at high speeds, where it contributes to hysteresis friction.
- Microtexture, which is governed by aggregate surface roughness, plays a dominant role in adhesion friction.

To improve friction design guidelines for various HMA mix designs, previous studies have investigated the relationship between pavement surface texture and friction performance (Kowalski et al., 2010; Li et al., 2010; Z. Wu & Abadie, 2018). However, further research is needed to quantify how different HMA mixture sizes and aggregate sources influence pavement macrotexture and microtexture, which directly impact friction performance. Field data has identified key variables that may contribute to low pavement friction, including:

- Traffic volume and pavement age
- Dolomite aggregate characteristics
- HMA mixture design type

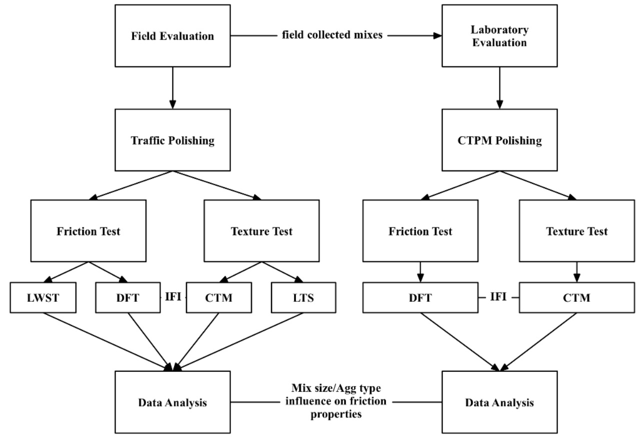


Figure 2.1 Experimental Plan for Field and Laboratory Study.

This study investigates the effects of these variables on friction performance to optimize Superpave HMA surface friction characteristics. The research is structured into two key experimental phases:

1. Field Testing:
   – In-situ pavement friction and texture measurements will be conducted using the DFT, CTM, and LTS across multiple road segments.
2. Laboratory Evaluation:
   – HMA mixture slabs will be prepared by reheating, remixing, and recompacting core samples collected from tested pavement sections.
   – Traffic polishing effects will be simulated using a Circular Track Polishing Machine (CTPM), followed by frictional resistance evaluation using DFT and CTM measurements.

The general research plan is illustrated in Figure 2.1. Through this investigation, the study aims to:

- Identify critical issues in current HMA surface mixture designs.
- Improve the understanding of friction-mix design relationships.
- Provide guidelines for restoring and maintaining pavement friction effectively.

This research will contribute to enhancing pavement safety, durability, and long-term performance, ultimately helping state agencies implement more effective pavement friction management strategies.

2.2 Field Evaluation

2.2.1 Friction and Mixture Design

A comparative investigation of 13 different DMFs was conducted to evaluate their pavement friction performance. Table 2.1 provides a summary of the contract information and FN40 friction data collected from pavement sections constructed using DMFs that included #11 dolomite. D1, D9, and D0 represent dolomite obtained from different sources.

Depending on the length of each pavement section and the corresponding road, the count of inventory FN40 datapoints

TABLE 2.1
Summary of Contract Information and Friction Results of DMFs using #11 Dolomite.

DMF Group	Construction		Friction			Aggregate Components	#11 Dolomite Source
	Contract	Year	Year	Avg FN40	% below 25		
	39977	2018	2019	50.65	0.00		
	36690	2020	2021	36.30	0.00		
	37796	2019	2020	40.14	7.69		
1	38668	2018	2021	21.70	100.00	#11 Dol, #12 Dol, #24 Dol Sand, -3/8" RAP, BH Fines	D1
	38632	2018	2019	53.66	0.00		
	39975	2018	2019	43.04	0.00		
	40520	2019	2021	35.31	28.57		
2	38646	2019	2022	26.63	66.67	#11 BF Slag, #11 Dol, #12 Dol, #24 CS Sand, #24 CR Sand, Superfine RAP, BH	D1
	40107	2020	2022	26.18	36.62		
	35144	2020	2023	26.10	0.00		
3	35144	2020	2022	21.45	100.00	#11, #12, 24 Stone Sand, Sand RAP, BH Fines, 24 Stone Sand, 24 Natural Sand	D9
	40106	2020	2022	24.83	57.14		
	41006	2020	2023	31.02	11.11		
4	41007	2021	2022	26.13	50.00	#9 Dol, #11 Dol, #12 Dol, #24 Dol Sand, Fractionated RAP, BH Fines	D1
5	41869	2021	2022	38.30	0.00	#11 Stone, #12 Stone, QA 24 Man Sand, -3/8" RAP, BH Fines	D1
	41871	2021	2023	34.67	11.11		
6	41008	2021	2022	13.13	100	#11 Dol, #12 Dol, #24 CS Sand, #24 CR Sand, Superfine RAP, BH	D1
7	41685	2021	2023	31.50	15.38	#11 Stone, #12 Stone, #24 CS Sand, #24 NS Sand, Fine RAP, BH	D0
	39963	2022	2023	28.35	0.00		
8	41540	2022	2023	29.02	46.15	#11 Dol, #12 Dol, #24 CS Sand, #24 CR Sand, Superfine RAP, BH	D1
	42055	2022	2023	27.83	12.50		
9	38651	2018	2021	30.32	27.78	#11 BF Slag, #11 Dol, #12 Dol, #24 Stone Sand, #24 Crushed Sand	D1
10	37295	2018	2021	36.03	11.11	#11 Cr. Stone, #12 Cr. Stone, QA #24 Stone Sand	D1
11	31597	2016	2021	18.83	86.67	#9 Dol, #11 Dol, Dol Sand, #24 Stone Sand, Fine RAP, BHF	D1
	31597	2016	2021	26.76	30.00		
12	39163	2018	2022	15.20	92.86	#11 Dol, #12 Dol, #24 Stone Sand, #24 Crushed Sand	D1
13	38655	2019	2022	43.41	0.54	#11, #12, #24 Stone Sand	D9

available for each construction varies. Therefore, the average number of FN40 data series is used to describe the impact of DMFs on pavement friction performance. A two-way Analysis of Variance (ANOVA) was conducted to evaluate the null hypothesis that there are no significant differences in the mean FN40 values among the thirteen DMF groups, while controlling for the main effects of pavement age (measured in months) at the time of the friction tests. A p-value of 0.2866 failed to reject the null hypothesis at a 5% significance level, indicating that the DMF main effect on pavement friction performance is not significant. The FN40 differences among the DMF groups were minor compared to the FN40 differences within the same DMF group.

A single DMF can be used for multiple contracts. Five of the DMFs listed in Table 2.1 are utilized across various contracts. Contracts that use the same DMF are grouped together and illustrated in Figure 2.2 with the FN40 designation. The legend provides the corresponding pavement age (0–5 years) at the time of the friction test in brackets. The DMF group numbers from Table 2.1 are labeled on the plot. Although the FN40 results for each pavement section were collected at different times following the surface construction (within the 0–5 years range), several observations suggest that low friction levels were more closely related to inconsistencies in aggregate quality rather than the DMFs themselves.

- A notable percentage of FN40 measurements under 25 was observed in pavement sections aged less than 5 years across all five DMF categories. This observation suggests that the mix design may not be the primary factor contributing to the low friction results.
- The construction of two US 36 sections (Reference Post [RP] 53.54–55.078 and RP 48.089–53.54) was completed in September 2016 under the same DMF and contract. However, FN40 data collected from these two sections in August 2021 show significant differences. More than 86% of the FN40 data from the section between RP 53.54 and RP 55.078 were below 25, while only 30% of low friction results were found in the adjacent road section.

INDOT has updated its mix design specifications from Superpave4 to Superpave5 for all new constructions with project lettings on or after September 2019. Figure 2.3 illustrates the differences in FN40 results between the two Superpave design categories. The blue boxes represent pavement sections that utilize Superpave5, while the orange boxes indicate pavements constructed using the Superpave4 design. According to the box plots, both high-friction and low-friction results were observed within each of the two categories. Overall, the change in the Superpave mix design did not significantly affect pavement friction performance within the first 0–5 years after construction.

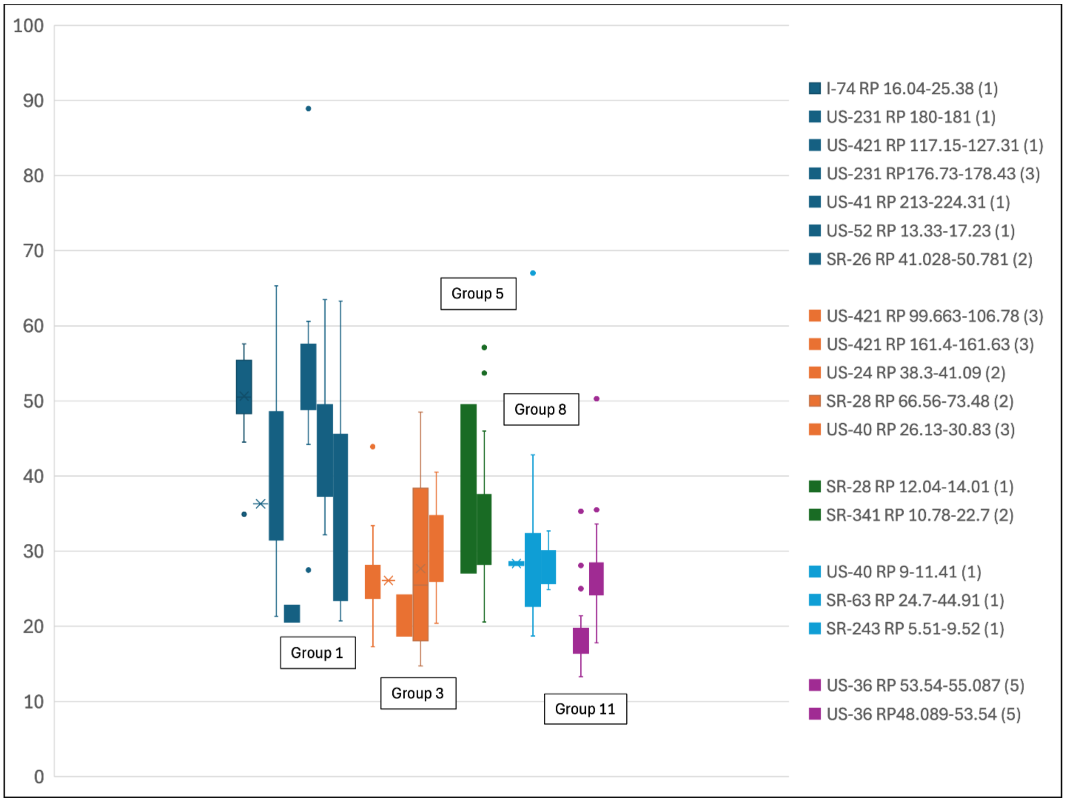


Figure 2.2 Inventory FN40 Data Grouped by DMF.

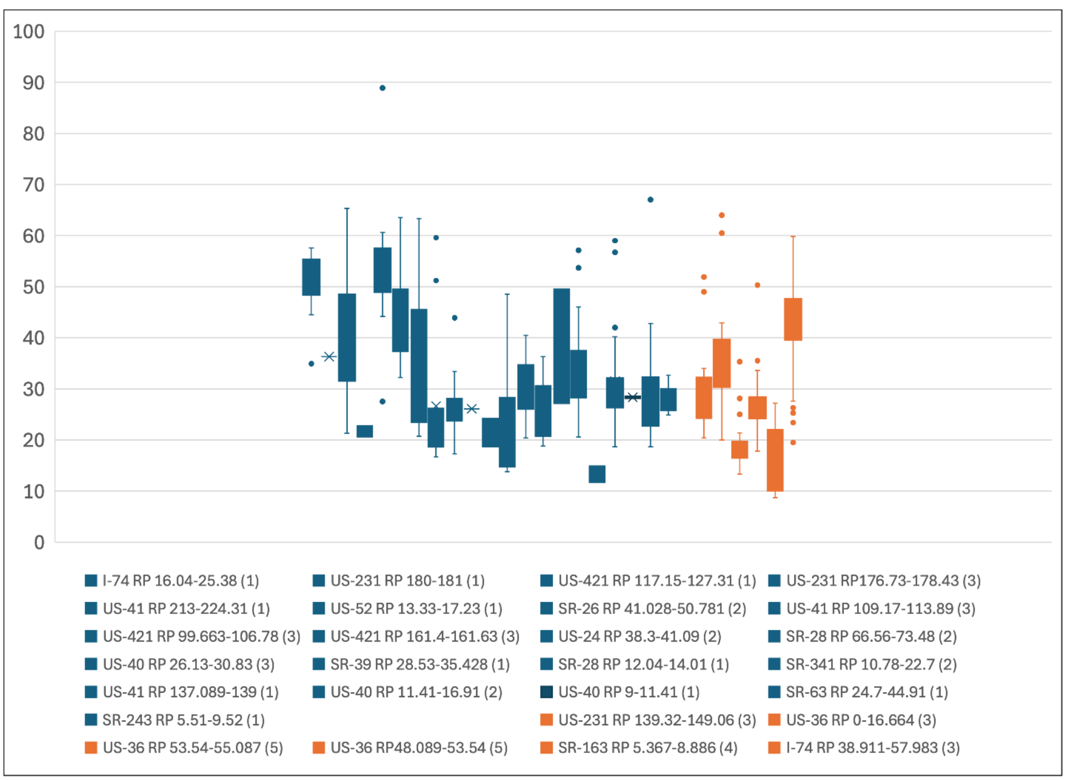


Figure 2.3 Inventory FN40 Data Grouped by Superpave 5 (blue) and Superpave 4 (orange) Categories.

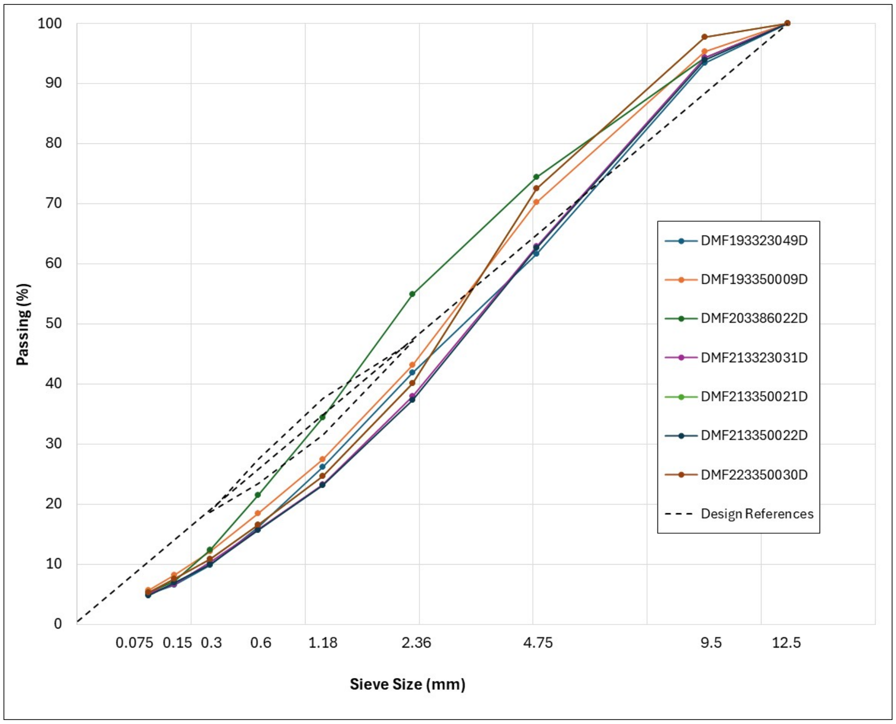


Figure 2.4 Gradation of Seven DMFs With 9.5 mm NMAS.

Seven DMFs examined in this study have a nominal maximum aggregate size (NMAS) of 9.5 mm. The gradations for these DMFs, plotted on a 0.45 power chart, are displayed in Figure 2.4. All seven gradations shown in the chart meet the control point requirements for a 9.5 mm NMAS pavement. Although one DMF falls outside the restricted zone, INDOT has eliminated the restricted zone from the aggregate gradation requirements. This finding suggests that the restricted zone is unlikely to be relevant to pavement friction.

2.2.2 Field Selection and Experimental Plan

After the discussion about the relationship between friction and DMFs, a field selection is proceeded to cover high-friction and low-friction roadway sections with different DMFs. Given the constraints imposed by weather and traffic conditions, 14 roadway sections within the Crawfordsville District were selected for coring and field testing. These sections represent a range of HMA mixtures, differing in mixture design type and aggregate blend sources. The selected sites include two commonly used Superpave wearing courses, Superpave 4 and Superpave 5 (9.5 mm and 12.5 mm mixture size), which are typical pavement designs in Indiana. The mixture size is defined as the NMAS of the aggregate in the mixture. The primary aggregate used in all 14 mixtures is #11 dolomite crushed stone, D1 or D9. Each selected roadway section covers between 3 and 16 miles of highway pavement. Figure 2.5 highlights these selected roadway segments (yellow lines) and specific test zones (red markers) within the Crawfordsville District.

To ensure uniform evaluation, straight pavement sections without sharp curves or intersections were selected for field measurements and coring. Each of the 14 road sections was divided into three test zones, spaced a few miles apart, resulting in a total of 42 test zones. In each test zone:

- 25 core samples (6 in. diameter) were extracted from the driving lane of the roadway.
- If adequate shoulder (SH) space was available, coring was performed there to obtain unpolished material for laboratory testing.
- In cases where shoulder space was insufficient, cores were taken from the lane center (LC), positioned between the left and right wheel paths (LWP and RWP) of the driving lane.

The assumption behind coring from the SH or LC is that these locations have experienced minimal traffic polishing, making them ideal for laboratory evaluation of the original material properties. Figure 2.6 provides representative images of selected coring locations.

To assess the impact of traffic wear on pavement friction performance, inventory FN data from LWST tests conducted at 40 mph were collected from the driving lane LWP within 1–2 years prior to this study. Surface texture measurements were conducted at four lateral locations within each test zone: LWP, LC, RWP, and SH. At each test location:

- LTS scans were performed to compare surface texture differences between LWP and coring (SH/LC) locations.
- CTM tests were conducted to assess macrotexture characteristics.
- DFT tests were performed to evaluate surface friction performance.

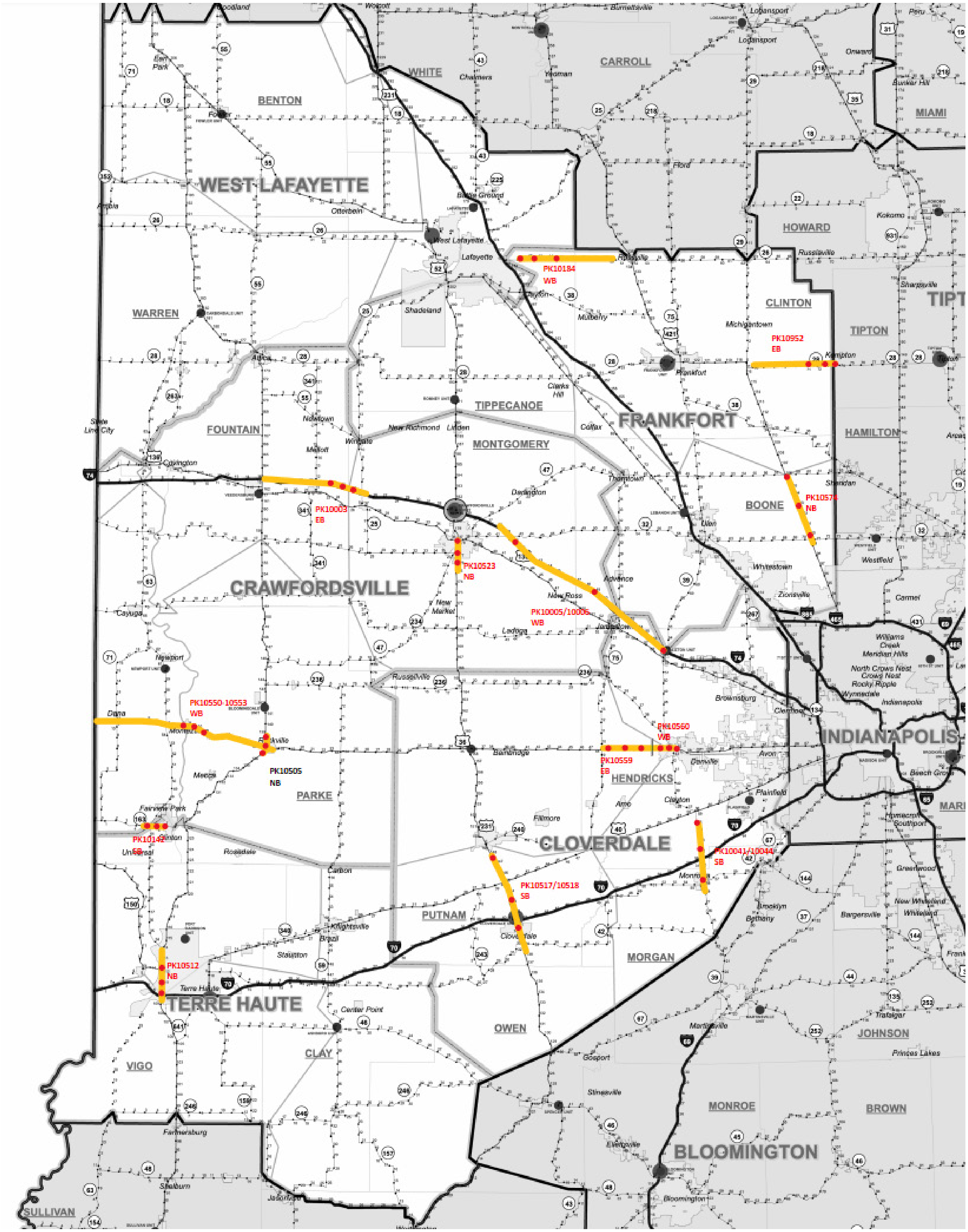


Figure 2.5 Locations of 14 Selected Roadway Sections (Yellow) and Sampled Test Zones (Red).

(a) Shoulder coring on US 421

(b) Lane center coring on US 36

(c) Lane center coring on I-74

Figure 2.6 Core Locations.

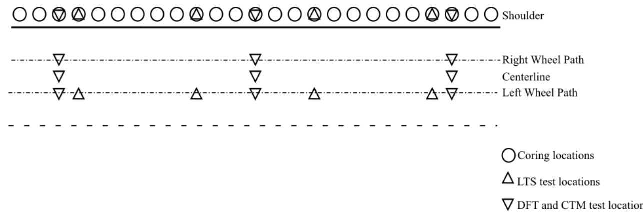


Figure 2.7 Layout of Coring and Field Measurements (Figure Not to Scale).

These tests were conducted at approximately 10 ft intervals within each test zone. Figure 2.7 illustrates the layout of coring and field measurements, showing the positioning of different test locations. Given that LTS, CTM, and DFT measurements require traffic control and temporary lane closures, field testing was carefully coordinated. Despite these logistical challenges, 40 out of 42 test zones were successfully tested over 14 test dates from April to June 2023. The collected field data was used to analyze friction performance variations, helping to refine HMA surface mixture design guidelines and develop effective strategies for restoring pavement friction.

2.2.3 Inventory LWST Friction Data

The network level friction testing program performed by INDOT provides routine FN40 data at one-mile intervals on all roadways throughout the state. The Indiana friction testing program utilizes LWST, shown in Figure 2.8, as the field friction test device at highway speeds. Following the ASTM E 274 standard, LWST is operated at a speed of 40 mph during a typical friction measurement for most of the time (ASTM, 2020b). During an LWST measurement, the system first sprays water ahead of an ASTM E 524 test smooth tire on the left side (ASTM, 2020c). Then, the test tire is fully locked, and the wet friction coefficient is calculated as the ratio between the test

Figure 2.8 Locked-Wheel Skid Tester (LWST) Oblique View.

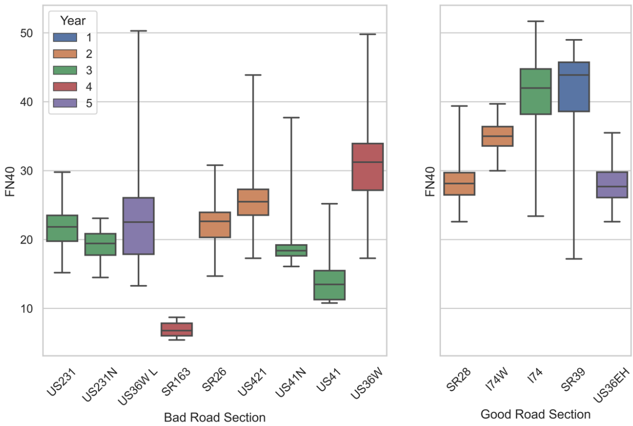


Figure 2.9 Boxplot of Inventory FN40 Data of 14 Road Sections.

tire longitudinal frictional force (converted from the measured torque) and the dynamic vertical force on the wheel. The output friction data of an LWST test is FN, which is the measured friction coefficient multiplied by 100. The test speed is stated along with the reported FN value. If the FN data was measured at a specific speed level other than the standard 40 mph, the equivalent FN at 40 mph of speed (FN40) is calculated and collected.

To trace problematic dolomite and other aggregate sources, the inventory FN40 friction data is first reviewed before the conduction of field tests that require traffic control and lane closure. The most recent FN40 data tested before the coring procedure time (April to June 2023) of each road section is initially collected to assist sample test zone selections. All 14 road sections were reconstructed within 5 years by the time of LWST friction testing. Boxplots in Figure 2.9 show the distribution of the most recent FN40 values from each tested mile, collected from the 14 selected road sections. The data is unbalanced as the lengths of 14 road sections vary. As shown in the box charts, different levels of friction performance were observed among the 14 road sections for 1–5 years of traffic polishing after construction. A test section is grouped as a “Good” (high friction) section if less than 10% of its FN40 data for each mile tested within the section, were below 25. Among the 14 select road sections, nine are categorized as “Bad,” and five are “Good.” Low friction results were discovered in two road sections on SR 26 and US 421 within 2 years after the recent pavement construction. Additionally, four more road sections were identified as having low friction values in the third year after surface construction.

The main purpose of this investigation was to evaluate the influence of mixture sizes and dolomite aggregate sources on the resulting frictional properties of HMA. Therefore, it was necessary to take control of the effect of various traffic polishing conditions (volume and year) among test data collected from different road sections. In FN40 inventory data, interstates are tested annually, while the remaining network highways are tested on a three-year cycle. To demonstrate traffic

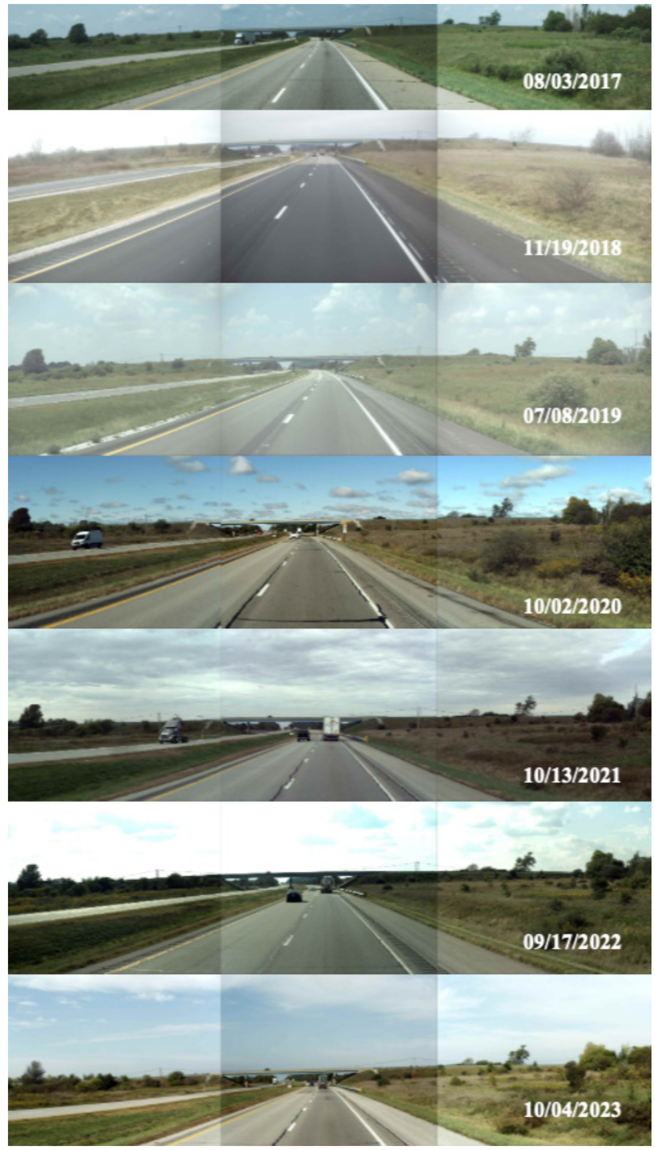


Figure 2.10 Roadway Images of I-74 at RP 20.6 WB Between 2017 and 2023.

wear effects on the reported FN40, westbound (WB) roadway images taken yearly at I-74 RP 20.6 between the years 2017–2023 are shown in Figure 2.10. An asphalt resurfacing project was reported completed in 2019 on I-74 from RP 16.04 to RP 25.38. However, the roadway image taken in 2018 shows that the resurface construction was completed and opened to traffic before the test date of November 19, 2018. In Figure 2.11, the corresponding 2017–2023 FN40 data distributions collected from the same nine-mile westbound pavement segment are displayed. In 2019 (the first year after construction), the average value of FN40 tested for this road section is the highest among 7 years of data. Although traffic polishing negatively impacts the FN40 value and developed cracks on the pavement surface in the year 2020–2023, this road section retained a sufficient friction level in all years between 2017 and 2023.

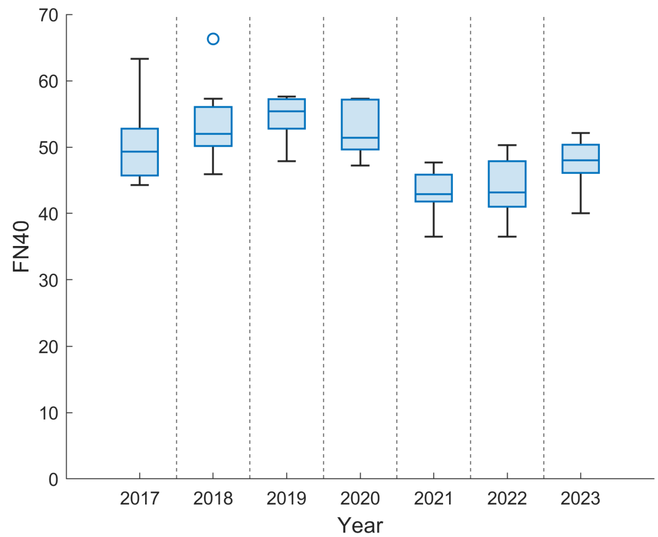


Figure 2.11 FN40 Variations on WB I-74 at RP 16.0-25.4 Between 2017 and 2023 (Resurface in 2019).

2.2.4 *LTS Measurement Results*

An LTS was used in this study to measure pavement surface texture depth and assess its relationship with friction performance. As previously mentioned, FN40 inventory friction data were obtained from the LWP of the driving lane, while the HMA mixture cores collected for laboratory testing were extracted from shoulder or lane center locations, which are considered unpolished. Therefore, a comparison of texture and friction data across different lateral locations was necessary to evaluate the impact of traffic wear on pavement surface characteristics.

Figure 2.12 shows the LTS Model 9200 by Ames Engineering, which was used for texture scanning. This device precisely captures surface texture information within a 76.2 mm × 101.6 mm scanning area at a vertical resolution of 0.015 mm and a sampling frequency of 1 kHz (Li et al., 2010). Each scan produces 101.6 mm two-dimensional (2D) profiles, and 10 lateral scans were performed at each measurement location, requiring approximately 3 min per scan. With a sampling spacing of 0.015 mm, the scanner effectively captures macrotexture (0.5 mm–50 mm) and part of microtexture (0.03 mm–0.5 mm), allowing for a comprehensive assessment of surface roughness.

Each LTS scan is initiated with a single button press, and upon completion, the LCD display on the device automatically provides the mean profile depth (MPD), computed from the 2D texture profiles based on ASTM E1845-23 standards (ASTM, 2023b). The scanned data are then transferred to a computer via an Ethernet interface for further analysis.

MPD is a widely used index for evaluating pavement macrotexture and is known to be a strong predictor of wet pavement friction (Li et al., 2010). The MPD calculation process is illustrated in Figure 2.13 and involves the following steps:

1. Extracting a 100 mm macrotexture profile from the original 2D scan, using a 0.5 mm low-pass 7th order Butterworth filter.

Figure 2.12 LTS Measuring on Asphalt Pavement Surface.

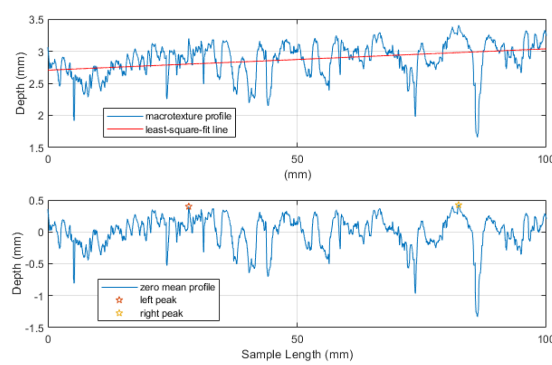
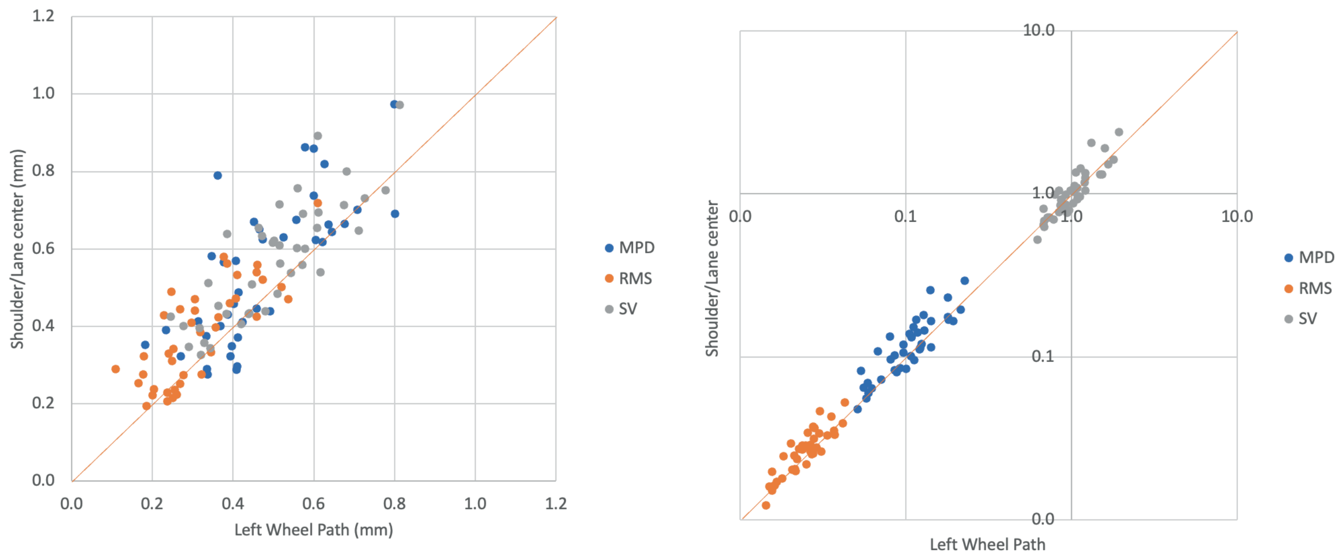


Figure 2.13 Pavement Macrotexture MPD Values.

2. Removing baseline variations by applying a least-square-fit line adjustment.
3. Identifying the peak values from the left and right 50 mm segments of the adjusted profile.
4. Computing MPD as the average of the two peak values.

Since MPD primarily considers positive depth peaks, two additional parameters, root mean square (RMS) texture depth and slope variance (SV), were also analyzed to provide a more comprehensive texture evaluation:

- RMS: Measures texture roughness, capturing overall depth variations (Equation 2.1).



(a) Macrotexture

(b) Microtexture

Figure 2.14 LTS Values at Coring Locations.

- SV: Assesses surface asperity sharpness, which contributes to hysteresis friction forces and is expected to correlate with FN40 values (Equation 2.2; Li et al., 2010).

$$RMS = \sqrt{\frac{\sum\left(y_i - Y_i\right)^2}{n}} \quad \text{Equation 2.1}$$

$$SV = \sqrt{\frac{\sum\left(\Delta y_i / \Delta x_i\right)^2}{n}} \quad \text{Equation 2.2}$$

For microtexture analysis, MPD, RMS, and SV were also computed using shorter baseline segments (12.5 mm) to better capture high-frequency surface features (Li et al., 2010).

Since LWP locations experience higher traffic loads, they are expected to exhibit greater texture deterioration compared to shoulder or lane center locations. This assumption was validated by analyzing LTS measurements across different pavement zones. Figure 2.14 presents comparative scatterplots for macrotexture (Figure 2.14a) and microtexture (Figure 2.14b) between LWP and coring locations. The results indicate:

- Pavement texture at LWP locations generally exhibits lower MPD, RMS, and SV values compared to SH or LC locations, where cores were taken and traffic exposure was minimal or absent.
- Traffic wear leads to a significant reduction in surface roughness at both macrotexture and microtexture scales.
- The degradation of microtexture is more subtle compared to macrotexture.

To quantify these differences, one-sample t-tests were performed to compare texture parameter data between the LWP and the SH and LC coring locations. The null hypothesis for each t-test states that the population means of the texture parameters at LWP and coring locations are equal. Table 2.2 summarizes the statistical results.

The following observations can be obtained from Table 2.2:

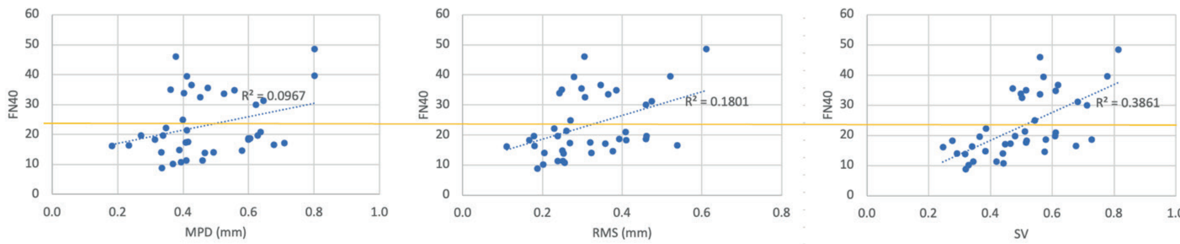
- Macrotexture parameters (MPD, RMS, SV) show significant degradation ($p < 0.05$) at LWP locations.
- Microtexture MPD and RMS exhibit significant differences between LWP and coring locations ($p < 0.05$).
- Microtexture SV is not significantly different ($p = 0.7974$), indicating that traffic polishing has a limited impact on microtexture asperity sharpness.
- Traffic exposure has a more pronounced impact on macrotexture properties than on microtexture. Further investigation is needed to assess the influence of aggregate source and mix design on pavement microtexture.

The relationship between LTS texture measurements and FN40 friction data was analyzed using R^2 values to assess correlation strength (Figure 2.15).

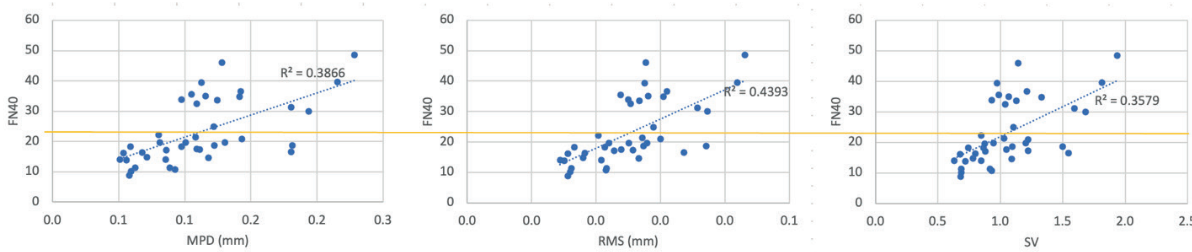
- Macrotexture SV exhibits a moderate correlation with FN40 ($R^2 = 0.3861$).
- Microtexture parameters (MPD, RMS, SV) all show moderate correlations with FN40, with R^2 values of 0.3866, 0.4393, and 0.3579, respectively.

TABLE 2.2
One Sample T-Test Comparing Texture Parameters.

Scales	Parameter	T Statistics	P-Value	STD Σ	95% CI	
	MPD	-3.6220	8.32e-4	0.1233	-0.1101	-0.0312
Macrotexture	RMS	-5.0477	1.07e-5	0.0805	-0.0899	-0.0385
	SV	-5.0477	1.18e-5	0.0879	-0.0978	-0.0416
	MPD	-2.8053	0.0078	0.0289	-0.0220	-0.0036
Microtexture	RMS	-2.7601	0.0088	0.0045	-0.0034	-0.0005
	SV	-0.2585	0.7974	0.1954	-0.0705	0.0545

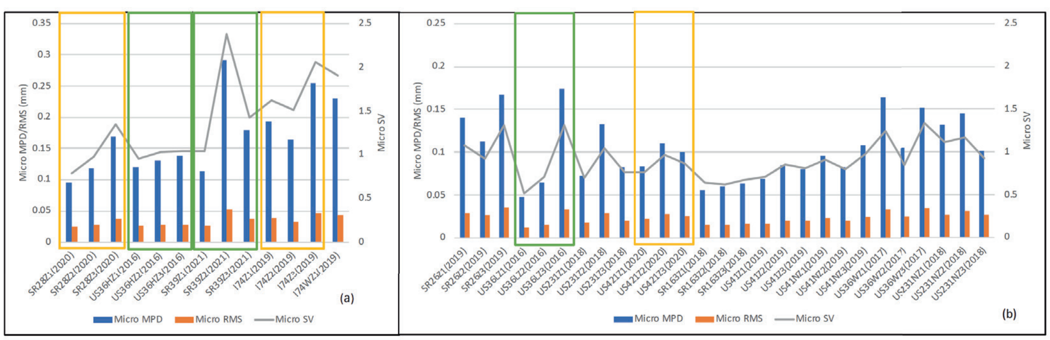


(a) Macrotexture



(b) Microtexture

Figure 2.15 Variations of Field FN40 Data With Corresponding LTS Measurements.



(a) Good Road Sections

(b) Bad Road Sections

Figure 2.16 Pavement Shoulder and Lane Center Microtexture vs. Mixture Design Types.

Although macrotexture parameters exhibit relatively low correlations with FN40, this does not necessarily indicate a weak link between surface texture and friction. The friction data were collected at different locations and times, and measurement discrepancies between friction test methods may contribute to variations in correlation strength.

To further examine microtexture variations, LTS measurements from shoulder and lane center locations were analyzed based on HMA mixture design types. The results indicate:

- All three mix design categories encompass both high and low-friction pavement sections, indicating that mixture design alone is not a definitive factor in distinguishing between "good" and "bad" pavement performance.
- No distinct differentiation in microtexture roughness is observed between dolomite aggregate sources (D1 vs. D9). Among the three pavements utilizing D9 dolomite (yellow-boxed), I-74 exhibits higher micro MPD values, whereas SR 28 and US 421 display lower micro MPD values, suggesting that additional factors influence microtexture variation beyond aggregate source alone.

ANOVA tests were conducted to assess the statistical significance of mixture type and dolomite source on microtexture properties (Table 2.3). The ANOVA results indicate the following:

- Microtexture RMS is significantly affected by dolomite sources ($p = 0.0385$).
- Mixture size (9.5 mm vs. 12.5 mm NMAS) does not significantly impact microtexture parameters.

TABLE 2.3
ANOVA Tests of the Influence of Mixture Size (9.5 mm/12.5 mm NMAS) and Dolomite Source (D1 and D9) on Microtexture Parameters.

Response	Factor	DF	F Statistics	P-Value
Micro- MPD	Mix Size	1	0.0738	0.7873
	Agg Source	1	2.4513	0.1257
Micro- RMS	Mix Size	1	1.0550	0.3109
	Agg Source	1	4.5968	0.0385
Micro- SV	Mix Size	1	0.8003	0.3766
	Agg Source	1	2.1618	0.1497

Given these findings, field CTM and DFT measurements were further analyzed to strengthen the texture-friction relationship and provide additional insights into pavement performance.

2.2.5 CTM Measurement Results

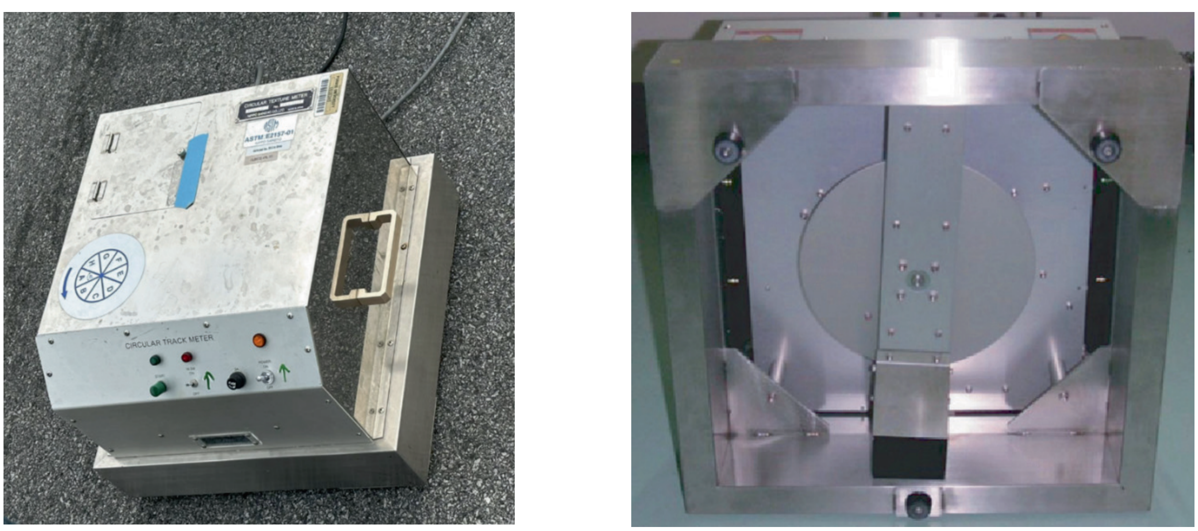
The CTM is a precision instrument designed to measure surface macrotexture MPD using a charge-coupled laser-displacement sensor, as standardized in ASTM E2157-15R24 (ASTM, 2024). Different views of the CTM are shown in Figure 2.17. From the bottom view (Figure 2.17b), the displacement sensor is mounted on a rotating arm, which revolves around a central axis at a fixed elevation of 80 mm above the measuring surface. During a typical measurement, the sensor rotates counterclockwise along a 284 mm-diameter circular track at a tangential velocity of 6 m/min, continuously capturing pavement texture data. The CTM is connected to a notebook computer, which is used for data collection, processing, and storage. Each CTM scan records MPD values for eight 111.5 mm arc segments, providing a detailed representation of pavement surface texture characteristics.

Since macrotexture MPD was measured using both the LTS and the CTM at the LWP and LC/SH locations, Figure 2.18 presents a comparative analysis of the measurement values obtained from the two devices. A one-sample t-test was conducted to assess whether or not the MPD values recorded by the LTS and CTM at both lateral locations are statistically equal. The null hypothesis of the test is that the MPD values recorded by the LTS and CTM are equal. The test result indicated that the null hypothesis is accepted at the 5% significance level. Therefore, the MPD measurements between the two devices are statistically equal. These results confirm that both the LTS and CTM effectively and precisely captured macrotexture MPD from the field pavement surfaces in this study, ensuring reliable texture assessment across different locations.

In Figure 2.19, the macrotexture MPD measurements collected by the CTM at various lateral locations, including LWP, LC, RWP, and SH, are compared. Additionally, the corresponding FN40 values for each of the 40 test zones are plotted as line segments for reference. A detailed analysis of the bar charts reveals the following key observations:

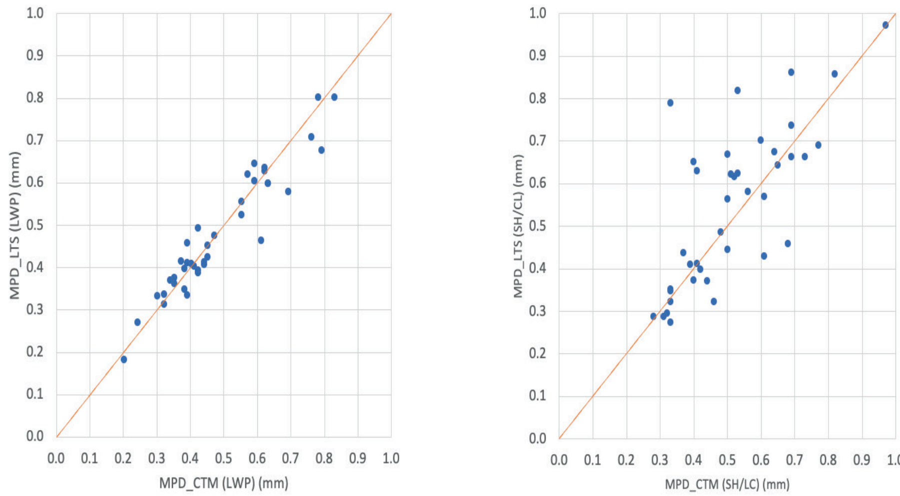
- In nearly half of the test zones across the 14 roadway sections, the MPD values at the LC were lower than those recorded at the corresponding wheel paths (LWP and RWP). This suggests that traffic loading may contribute to differences in macrotexture depth over time.
- A higher MPD at LWP does not necessarily correspond to an increase in FN40 friction values. The comparison indicates no clear positive correlation between macrotexture MPD and inventory FN40 data, reinforcing the point that factors beyond macrotexture depth influence pavement friction performance.

To illustrate pavement macrotexture variations across different lateral locations, Figure 2.20 (for "Good" pavement sections)



(a) Top-Side View (b) Bottom-Side View

Figure 2.17 Circular Track Meter (CTM).



(a) LWP Locations (b) Shoulder/Lane Center Locations

Figure 2.18 Macrotexture MPD Measured by LTS and CTM at Different Locations.

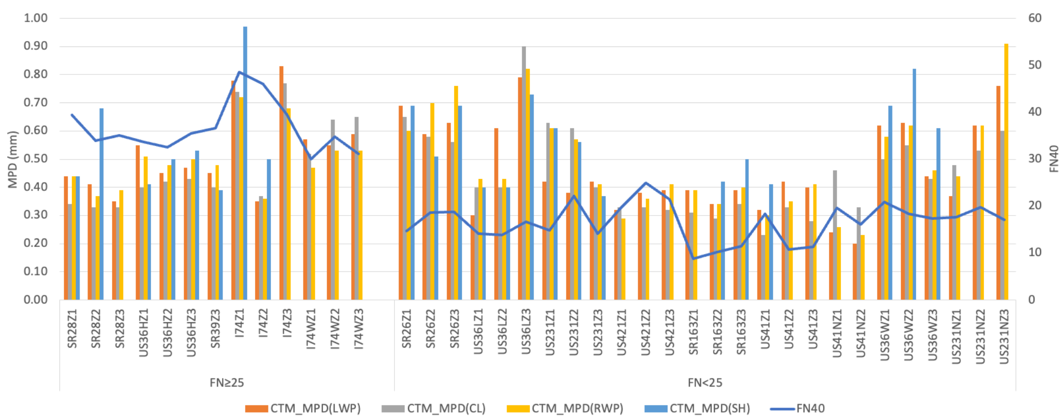


Figure 2.19 Relationship Between CTM Measured Macrotexture MPD and FN40 Data.

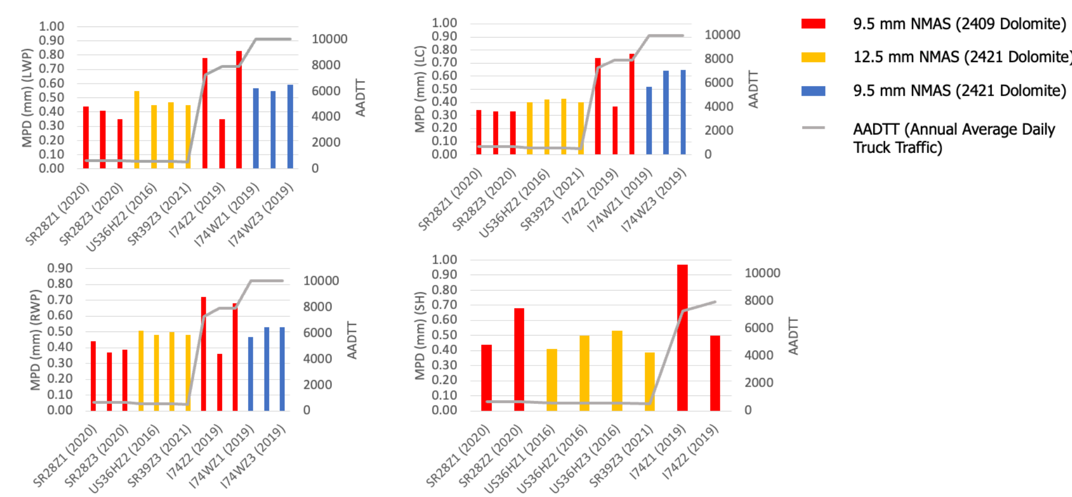


Figure 2.20 Field CTM Measurements of “Good” Road Sections.

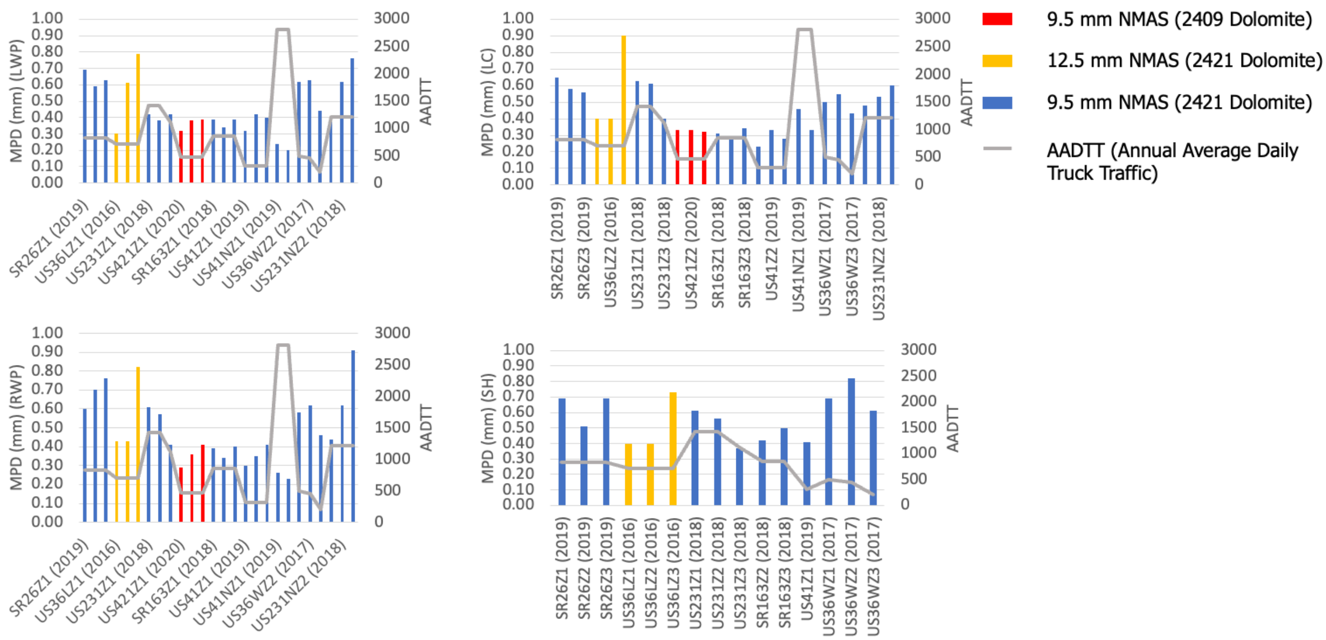


Figure 2.21 Field CTM Measurements of "Bad" Road Sections.

and Figure 2.21 (for "Bad" pavement sections) compare the average macrotexture MPD values measured by the CTM. These values are analyzed alongside the Annual Average Daily Truck Traffic (AADTT) data for each road section. AADTT and construction year serve as indicators of traffic volume and pavement age, helping to assess their impact on macrotexture characteristics across the 14 selected road sections.

Key observations from the analysis include:

- In 24 out of 39 test zones measured by CTM, LC MPD values were lower than those measured at the LWP and RWP. This suggests that, contrary to expectations, the LC—typically a less-trafficked area—may have been subjected to unexpected traffic polishing and/or transverse paver segregation. It should be noted that only a small part of these lane centers with an MPD lower than wheel paths were selected as coring locations.
- Conversely, MPD values at the SH locations, if exist, were consistently higher than those recorded at the wheel paths in these same sections. This highlights the relative preservation of surface texture in areas not directly exposed to tire wear. It should be noted that the 10-foot-wide shoulders on I-74 were likely paved separately and with a different asphalt mix from the travel lanes.
- A notable interaction between traffic volume (AADTT) and pavement age was observed, significantly influencing macrotexture MPD values, regardless of mixture size and aggregate type. Older sections and those with heavier traffic loads exhibited greater reductions in macrotexture depth, indicating a strong correlation between traffic-induced polishing and pavement texture degradation over time.

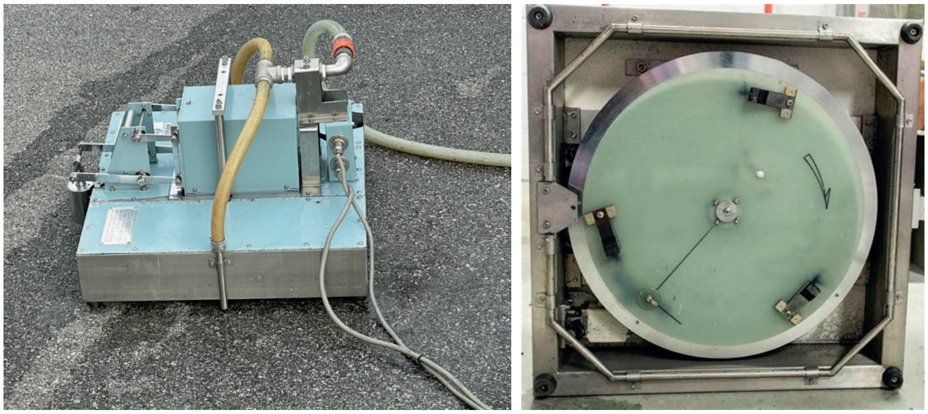
2.2.6 DFT Measurement Results

The DFT, shown in Figure 2.22, is utilized to measure the dynamic friction coefficient (DF) following ASTM E1911-19 (ASTM, 2019). This portable device consists of a horizontally spinning disk equipped with three spring-loaded rubber sliders. During operation, the sliders come into contact with the pavement surface, forming a 284 mm-diameter measurement track, which is the same diameter used for CTM measurements. This consistency allows for the calculation of the International Friction Index (IFI) in both field and laboratory settings.

To initiate a DFT test, the spinning disk accelerates to a linear speed of 70 kph, while a water supply unit continuously delivers water to the surface. Once the designated speed is reached, the disk drops down, applying a 1.2 kg (2.65 lb) load on each rubber slider. The data collection process requires an attached notebook computer, which records the friction coefficient at various speeds. In this study, measurements were taken at 20 kph (DF20) and 40 kph (DF40).

DFT20 is widely recognized as a key parameter for assessing pavement friction performance, which refers to the coefficient of friction measured with Dynamic Friction Tester at a speed of 20 km/h. According to ASTM E1960 (ASTM, 2023a), a sufficiently skid-resistant pavement surface should have a DFT20 value greater than 0.3 (but not exceeding 0.9). Figure 2.23 presents the distribution of DF20 values measured at different lateral locations in the 40 test zones. Key observations include:

- Wheel Path Locations (LWP and RWP):
  - 63.4% (LWP) and 70.7% (RWP) of measurements exceeded 0.3, indicating that most wheel path areas retained sufficient DFT20 values despite wear.
- LC and SH Locations:
  - A higher percentage (87.8%) of DF20 measurements at LC exceeded 0.3, while all DF20 values at shoulder locations fully satisfied the threshold.



(a) Top-Side View (b) Bottom-Side View

Figure 2.22 Dynamic Friction Tester (DFT)

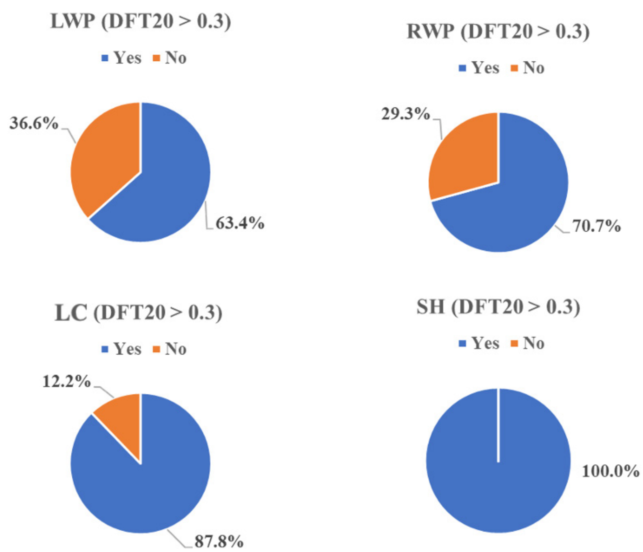


Figure 2.23 Distributions of DFT20 at 42 Test Zones.

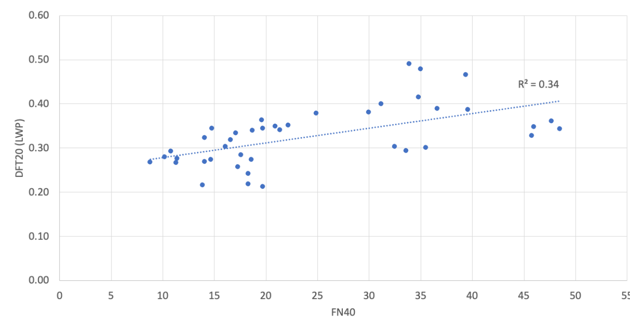


Figure 2.24 Scatterplot of Friction Measured by DFT (DF20) and LWST (FN40).

- This confirms that shoulder materials remained unpolished, making them ideal for unaffected laboratory texture and friction analysis.
- However, if core samples were collected from lane center locations, traffic effects may not be fully eliminated, affecting friction evaluations in laboratory settings.

A Pearson's correlation test was conducted to examine the relationship between DF20 (measured using DFT) and FN40 (inventory friction number from LWST tests). As shown in Figure 2.24, the results indicate a moderate correlation ($R^2 = 0.34$) between the two friction measurement methods.

Two two-sample t-tests were conducted to evaluate DFT20 variations based on:

1. HMA mixture size (9.5 mm vs. 12.5 mm)
2. Aggregate type (D9 vs. D1 dolomite)

Figure 2.25 and Figure 2.26 present a comparison of DFT20 (LWP) results, evaluating the impact of HMA mixture sizes and aggregate types, respectively. The pavement order remains consistent between both figures. The key findings from the two-sample t-tests are summarized below:

- Mixture Size Comparison:
  - The 9.5 mm NMAS surface mixtures exhibited higher mean DFT20 values compared to the 12.5 mm NMAS group. However, this difference was not statistically significant ($p = 0.29 > 0.05$), indicating that mixture size alone does not substantially impact wet friction performance at LWP locations.
- Aggregate Type Comparison:
  - Pavements incorporating D9 dolomite demonstrated significantly higher DFT20 values than those constructed with D1 dolomite ($p = 0.002 < 0.05$).
  - These findings support previous observations that D9 dolomite pavements tend to exhibit greater microtexture roughness and higher wet friction values.
  - The results reinforce the positive correlation between DFT20 friction values and microtexture roughness, highlighting the influence of aggregate type on pavement friction characteristics.

The age of the pavement (length of operation) was analyzed to determine its effect on DFT20 performance. An ANOVA

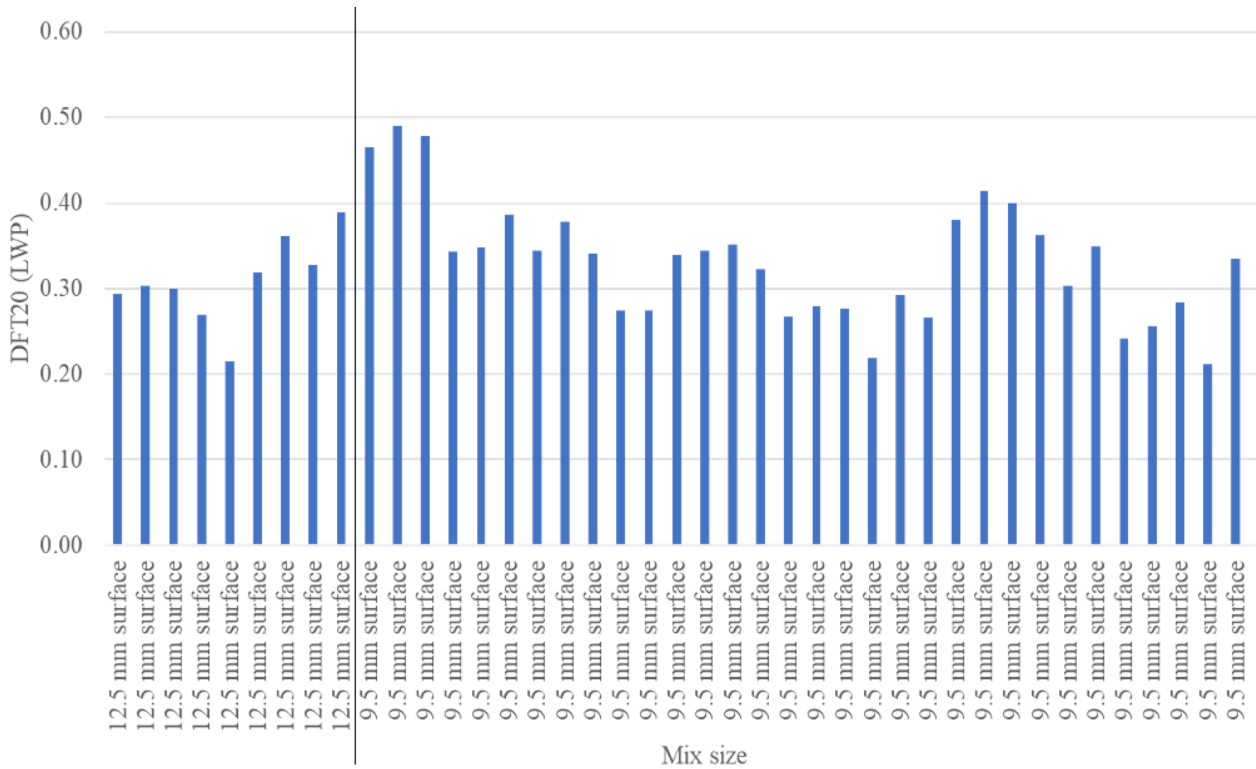


Figure 2.25 DF20 Variation With Different Mixture Sizes.

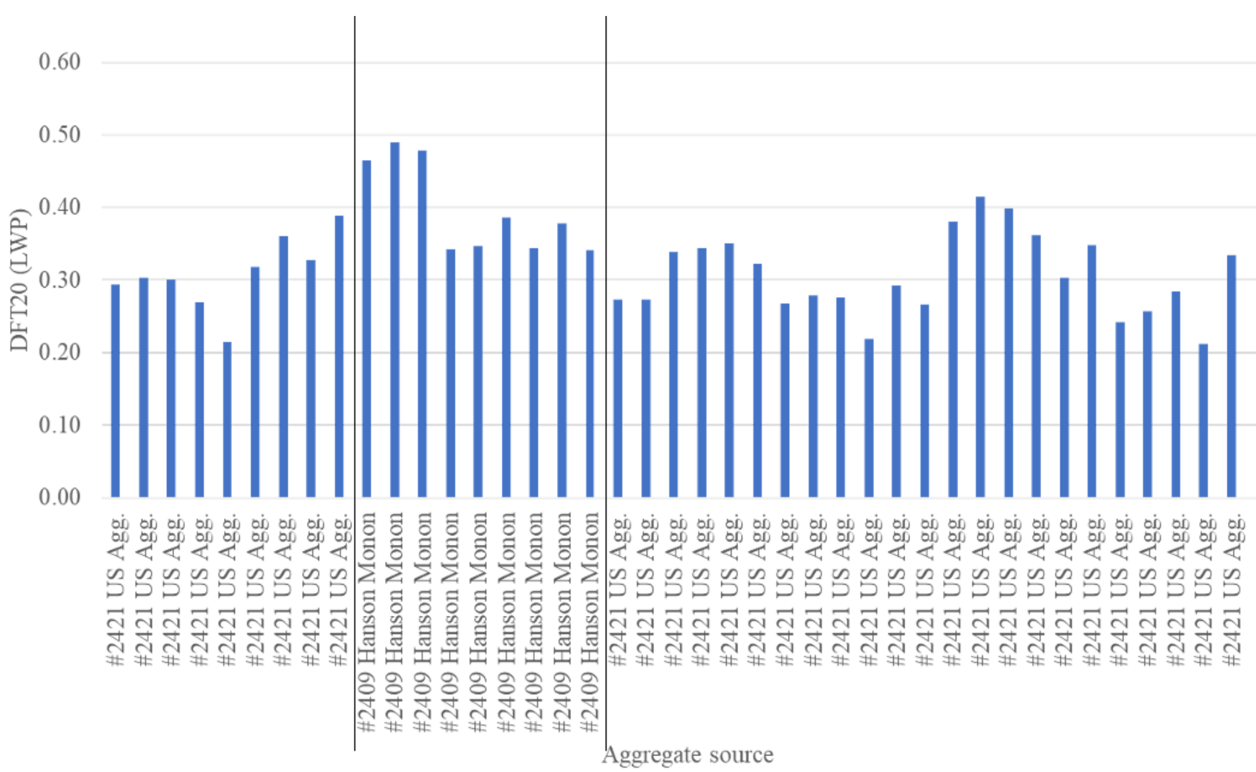


Figure 2.26 DF20 Variation With Different Aggregate Types.

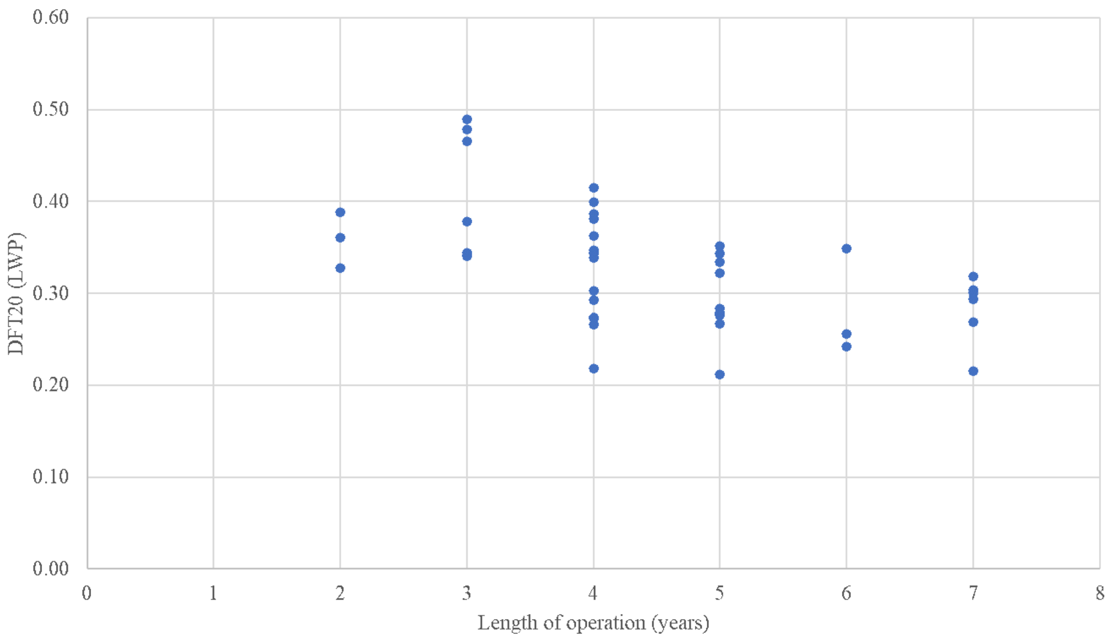


Figure 2.27 DF20 Variation With Different Length of Operation.

TABLE 2.4
Association Between DF20 and Influence Factors.

Variable	Statistical Test	Null Hypothesis	Inference/ Conclusion
DF20 vs. FN40	Pearson's Correlation		Moderate Correlation
DF20 vs. Aggregate Type	Two-Sample t-Test	$\mu_{D9} = \mu_{D1}$	D9 has a significantly higher DF20
DF20 vs. Mixture Size	Two-Sample t-Test	$\mu_{9.5mm} = \mu_{12.5mm}$	No significant difference
DF20 vs. Pavement Age	ANOVA	$\mu_{1yr} = \mu_{2yr} = \mu_{5yr}$	Significant decline after 3 years

test comparing DFT20 values across six pavement age groups revealed a statistically significant decline in friction after 3 years of operation ($p = 0.000923 < 0.05$), as shown in Figure 2.27. The relationships between DF20 and various factors are summarized in Table 2.4.

These findings confirm that pavement age, aggregate type, and microtexture roughness significantly impact DFT20 values, with D9 dolomite pavements consistently exhibiting better friction performance.

2.2.7 The International Friction Index (IFI)

The Permanent International Association of Road Congress (PIARC) introduced the IFI to standardize and harmonize pavement texture and friction measurements across different evaluation methods. The IFI integrates pavement macrotexture and wet pavement friction performance, thereby accounting for the influence of both microtexture and macrotexture on friction. In this study, DF20 (measured by DFT) and macrotexture MPD (measured by CTM) were used to compute IFI parameters. The speed constant (S_p) and the calibrated wet friction number (F60) were calculated as follows (ASTM, 2023a):

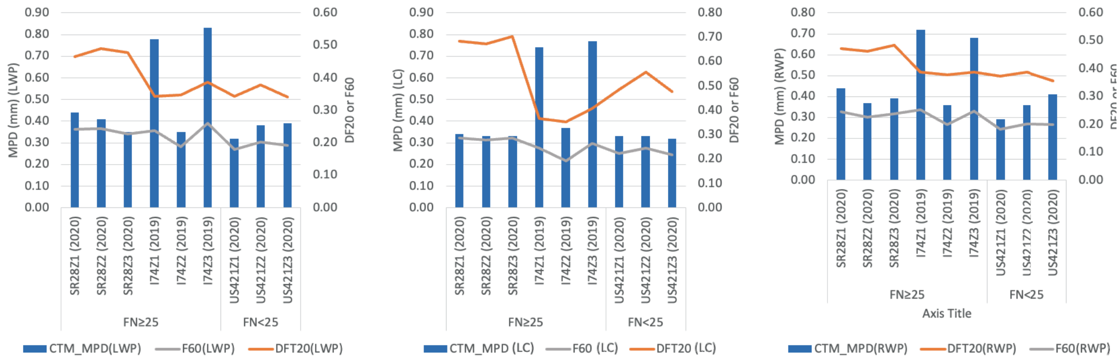
$$S_p = 14.2 + 89.7MPD \qquad \text{Equation 2.3}$$

$$F60 = 0.081 + 0.732DF_{20}exp\left(-\frac{40}{14.2+89.7MPD}\right) \qquad \text{Equation 2.4}$$

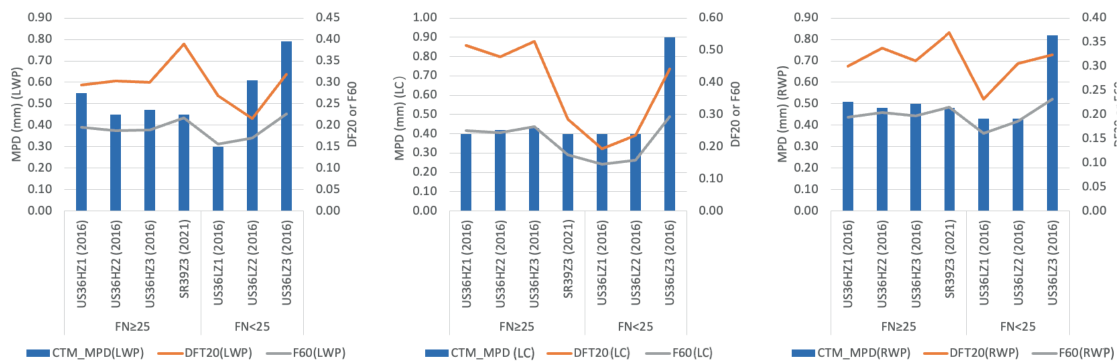
The IFI parameters, F60 and S_p, are widely recognized for their effectiveness in predicting the speed dependence of wet pavement friction performance. Figure 2.28 illustrates the relationship between MPD, DF20, and F60 across different pavement sections constructed with various mixture types. The following can be observed in the figure:

- F60 shows a stronger correlation with MPD than DF20, indicating the complex interplay between measuring speed, macrotexture, and friction values, as represented in Equation 2.4.
- Differences in IFI parameters across various surface mixtures highlight the impact of aggregate type and mixture design on long-term pavement friction performance.

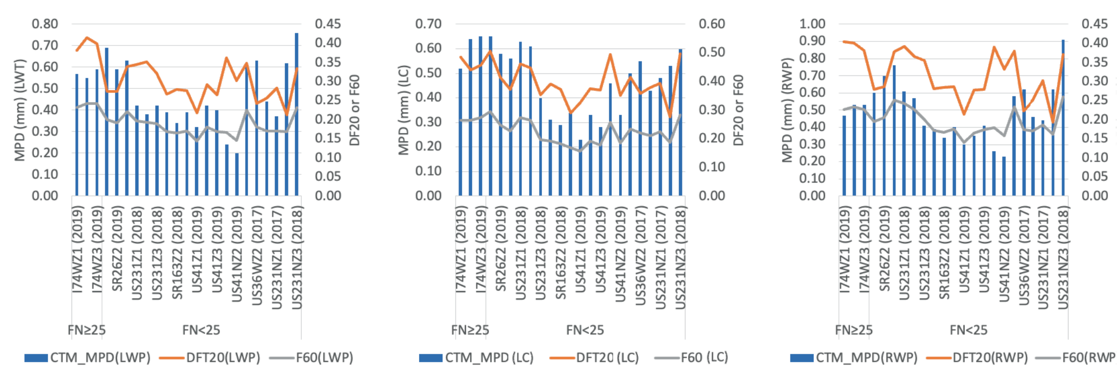
The evaluated pavement sections had been exposed to traffic wear for different durations, affecting both pavement friction and texture roughness. Results indicate that traffic-induced polishing effects are significant and cannot be ignored. To control for the influence of traffic wear, a laboratory-based accelerated polishing process was conducted. Friction and texture measurements were performed at various polishing stages using



(a) 9.5 mm NMAS D9 Dolomite



(b) 12.5 mm NMAS D1 Dolomite



(c) 9.5 mm NMAS D1 Dolomite

Figure 2.28 Relationship Between Field CTM, DFT Measurements, and F60.

core samples extracted from relatively "unpolished" locations (e.g., shoulder and lane center) of each road section. This approach allows for a more accurate evaluation of intrinsic material properties without the interference of traffic-induced degradation. By integrating field-based IFI measurements with controlled laboratory testing, this study aims to provide comprehensive insights into pavement texture-friction relationships, ultimately informing better mix design practices and maintenance strategies for long-term friction.

2.3 Laboratory Evaluation

2.3.1 Testing Mixture Slab Preparation

In this study, 28 HMA mixture slab specimens were prepared for two rounds of laboratory friction evaluation tests in accordance with Indiana Test Method (ITM) 221 (Kowalski et al., 2010). As previously discussed, field measurements and core extractions were performed in three designated zones at each

(a) HMA Layer Cores (b) Polished Testing Slab

Figure 2.29 HMA Surface Layer Cores and Testing Slab.

test site. Each test round included 14 slabs, with each slab representing one of the 14 test roadway sections. Due to time and budget constraints, friction and texture testing were conducted on samples from two of the three zones.

Each HMA testing slab was 500 mm × 500 mm (20 in. × 20 in.) with a thickness of 1.5 in. and was produced using surface mixture samples extracted from designated test zones. The preparation of each slab followed a two-step process:

1. Core Sample Processing: Field-collected core samples were cut to remove any material below the Superpave HMA surface layer to ensure that only the relevant surface mixture was used.
2. Softening, Remixing, and Compaction: The surface layer material was softened, remixed, and compacted according to the density and air void specifications outlined in DMFs used in the original field pavement construction projects (McDaniel et al., 2019).

To ensure the representation of different mix designs and aggregate sources, the 14 slabs in each test round were categorized as follows:

- Three slabs: D9 dolomite with 9.5 mm mix size
- Three slabs: D1 dolomite with 12.5 mm mix size
- Eight slabs: D1 dolomite with 9.5 mm mix size

Figure 2.29 illustrates the preparation process, showing cut Superpave HMA surface layer material from 25 core samples and a fully prepared and polished HMA testing slab in a wooden mold. Given that multiple test zones were sampled within each roadway section, variability between different locations was analyzed by comparing friction test results across the two replicate test rounds. This comparison provided insights into potential inconsistencies in friction performance based on mixture composition, aggregate source, and field aging effects. By reconstructing field pavement surfaces under controlled laboratory conditions, this approach ensured a consistent evaluation of HMA surface mixture performance, allowing for an accurate assessment of texture-friction relationships and the effects of material composition on pavement friction.

2.3.2 CTPM Polishing Procedure

The CTPM, shown in Figure 2.30, was utilized in this study to simulate vehicular traffic wear on HMA testing slabs. Developed by the National Center for Asphalt Technology, the CTPM conditions pavement surfaces by applying repeated polishing cycles using three rotating wheels. The machine polishes a doughnut-shaped area with a diameter of 284 mm (11.2 in.), replicating the surface wear caused by real-world traffic. Throughout the polishing process, water is continuously sprayed onto the test slab surface to remove debris and maintain uniform conditioning.

The polishing duration varies depending on the material being tested. In this study, each test slab underwent 100,000 polishing cycles, equivalent to 300,000 wheel passes, to simulate long-term surface wear and reach terminal friction levels.

- Testing Slab Specifications:
  - Planar dimensions: 500 mm × 500 mm (20 in. × 20 in.)
  - Thickness: 38 mm (1.5 in.)
  - Target air void: 7%, achieved using a kneading-compaction procedure

Figure 2.30 Circular Track Polishing Machine (CTPM).

To monitor the progressive change in surface texture and friction resistance, measurements were conducted at seven predefined testing stages throughout the polishing process.

- Polishing Intervals (Testing Stages):
  - 0 cycles (initial surface, unpolished)
  - 4,500 wheel passes
  - 37,500 wheel passes
  - 75,000 wheel passes
  - 150,000 wheel passes
  - 225,000 wheel passes
  - 300,000 wheel passes (terminal friction)

At the end of each predefined polishing interval, the CTPM was stopped, and the slab was removed and dried for evaluation. The surface texture was measured using the CTM, while friction resistance was assessed using the DFT. By incorporating controlled laboratory polishing cycles, this procedure enabled a comprehensive evaluation of the texture-friction relationship, helping to simulate real-world pavement wear conditions and improve the interpretation of HMA mixture durability and performance.

2.3.3 CTM and DFT Measurement Procedure

To evaluate the macrotexture and friction characteristics of the HMA testing slabs throughout the seven stages of the simulated polishing process, a combination of CTM and DFT measurements were conducted. These measurements provided insights into surface texture evolution and wet friction performance under accelerated wear conditions.

The measurement devices and their functions are as follows:

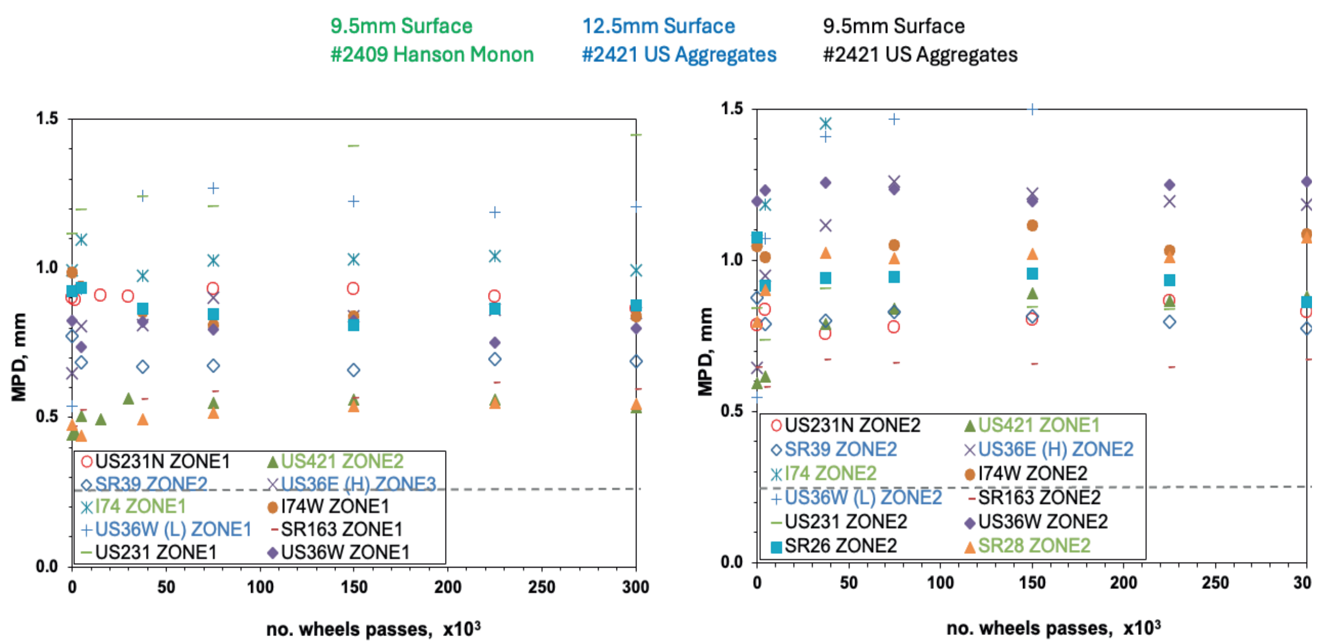
- CTM:
  - Measures macrotexture MPD
  - Achieves a vertical resolution of 3 μm
  - Captures surface texture over the same polished area subjected to CTPM wheel passes
- DFT:
  - Evaluates wet friction performance
  - Measures the coefficient of dynamic friction based on the tangential speed of a rotating rubber slider
  - Conducted on the same polished footprint used by the CTPM's three rubber tires

2.3.4 Laboratory Evaluation Results

Figure 2.31 presents the macrotexture MPD measurements obtained using the CTM at various stages of the CTPM process. The results from the two test rounds indicate the following key observations:

- The MPD values of the final slab surfaces (after 300,000 wheel passes) were not necessarily lower than those recorded on the initial slab surfaces.
- Throughout the CTPM polishing process, all 28 testing slabs maintained an MPD above 0.25 mm, demonstrating sufficient macrotexture levels for adequate pavement friction performance.
- This suggests that macrotexture roughness does not deteriorate significantly with increased polishing cycles.

To assess how well the laboratory-prepared slabs represented their source field pavements, Figure 2.32 compares the MPD



(a) First Round CTPM Test (b) Second Round CTPM Test

Figure 2.31 Slab Macrotexture MPD Measurements From the CTPM Tests.

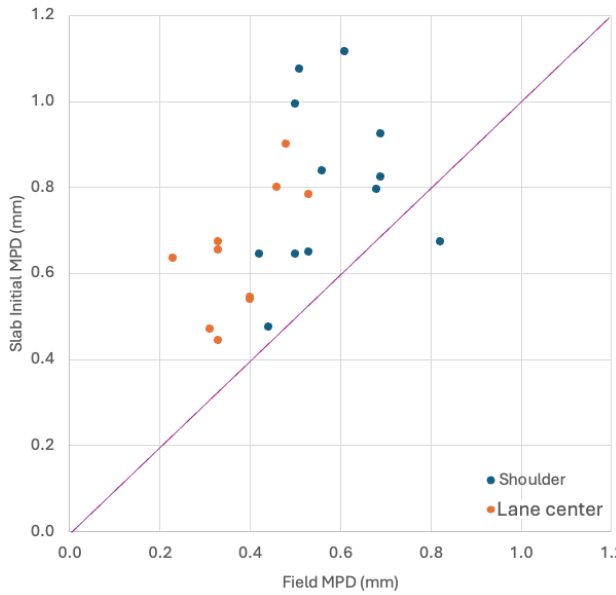


Figure 2.32 MPD From the Field Coring Locations vs. MPD in the Lab on Initial Slab Surfaces.

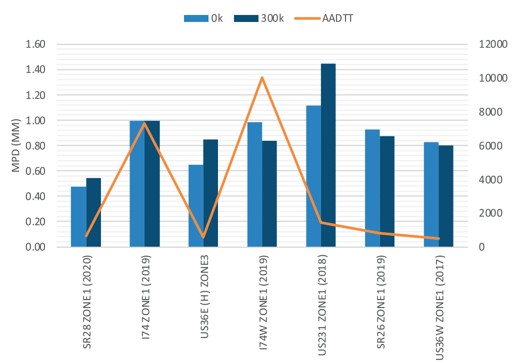
values from field pavement surfaces with initial MPD values from the reconstructed slabs:

- In most cases, initial slab MPD values exceeded the MPD of the corresponding source pavement.
- This discrepancy suggests that the laboratory-prepared slabs were not identical to the original pavement surfaces, which may lead to differences between field and lab findings.

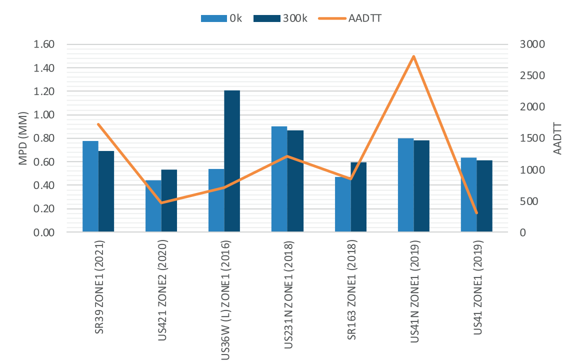
Seven of the 14 road sections lacked sufficient shoulder space for coring, so mixture samples from these locations were extracted from the driving lane center. To evaluate traffic effects on pavement texture, MPD values were analyzed in relation to AADTT before and after polishing (Figure 2.33). Results indicated:

- A positive correlation between AADTT levels and both initial and postpolishing MPD values.
- Even though the slabs were sourced from unpolished areas, traffic volume still had a measurable impact on macrotexture characteristics.

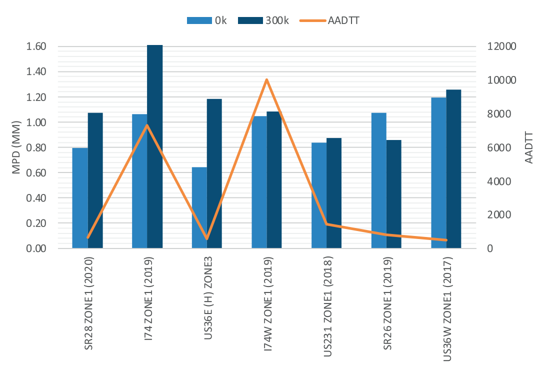
The limited correlation between FN40 inventory friction data and MPD at LWP locations prompted a comparison between



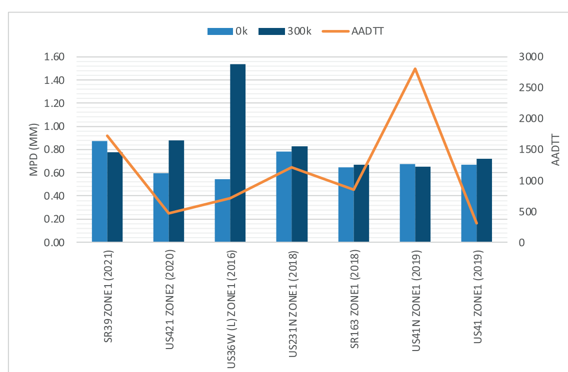
(a) First Round CTPM Test, Cores From Shoulder



(b) First Round CTPM Test, Cores From Lane Center

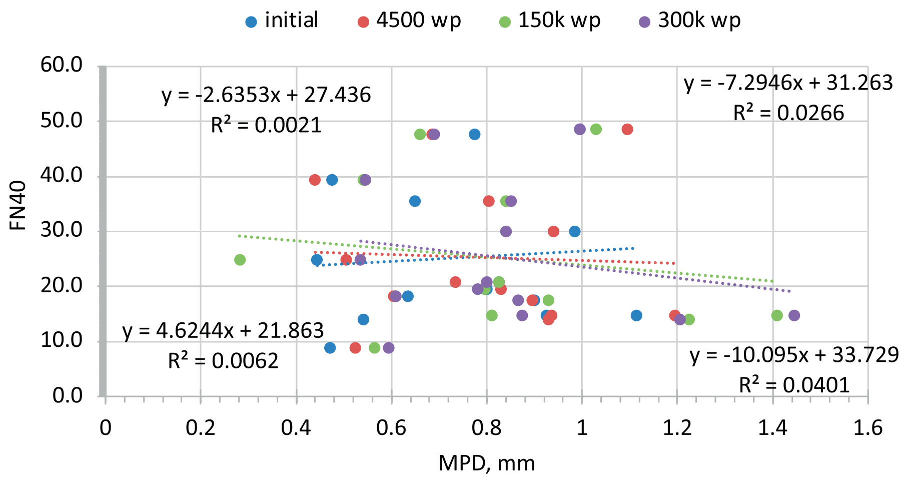


(c) Second Round CTPM Test, Cores From Shoulder

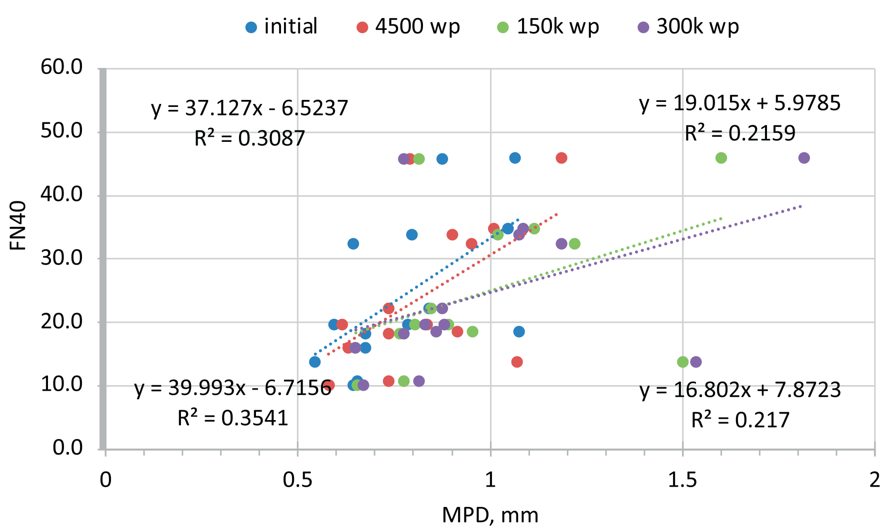


(d) Second Round CTPM Test, Cores From Lane Center

Figure 2.33 MPD and AADTT Values on the Initial and Ultimate Slab Surfaces in Test Round 1 (a and b) and Test Round 2 (c and d).



(a) First Round CTPM Test



(b) Second Round CTPM Test

Figure 2.34 Field FN40 Data vs. Slab Macrotexture MPD in the CTPM Tests.

FN40 values and lab-measured MPD (Figure 2.34). The results revealed:

- In the first test round, the correlation was weak.
- In the second test round, a moderate positive correlation was observed between MPD values (before and after 4,500 wheel passes) and FN40 friction data.
- This suggests that the second set of laboratory-prepared slabs more closely resembled the field pavement conditions at LWP locations when the FN40 friction data were originally recorded.

The DFT was used to measure the surface friction properties over the same testing slab footprint as the CTM measurements.

- As shown in Figure 2.35, DF values decreased rapidly with an increasing speed between 20 kph and 60 kph.
- DF40 (measured at 40 kph) was used for comparison, as it provided more robust results than DF20.

Figure 2.36 presents DF40 values recorded at different polishing stages across two test rounds:

- For each slab, DF40 initially increased during the early polishing stages (up to 4,500 wheel passes) before gradually declining with additional polishing cycles. This trend is expected, as the asphalt coating on the aggregate wears away under repeated tire contact. As polishing continues, the exposed aggregate begins to wear down, leading to a gradual decline in DF40.
- The final DF40 values (after 300,000 wheel passes) were the lowest recorded for all slabs, reflecting the long-term effects of aggregate polishing on friction.

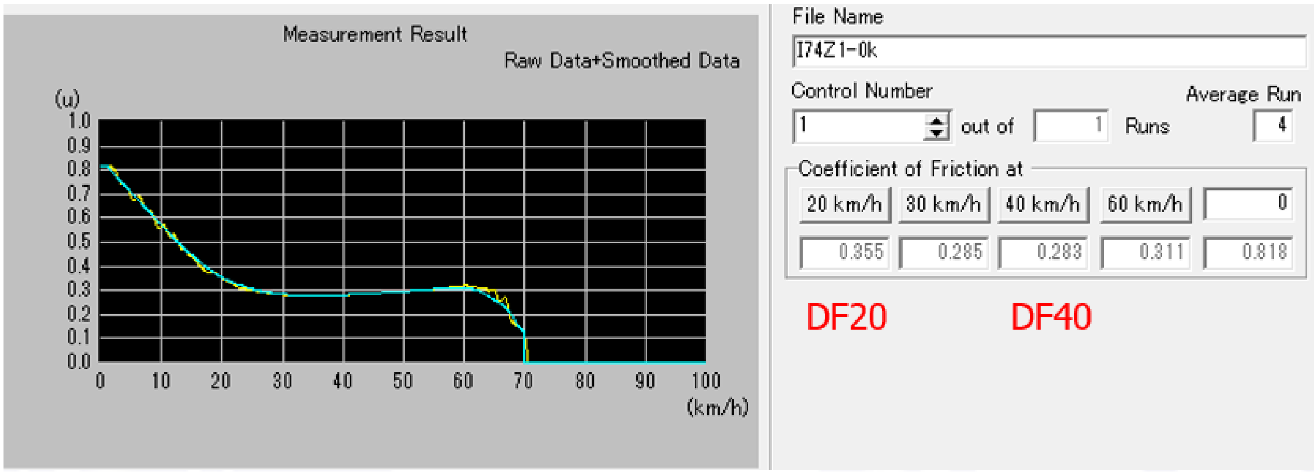
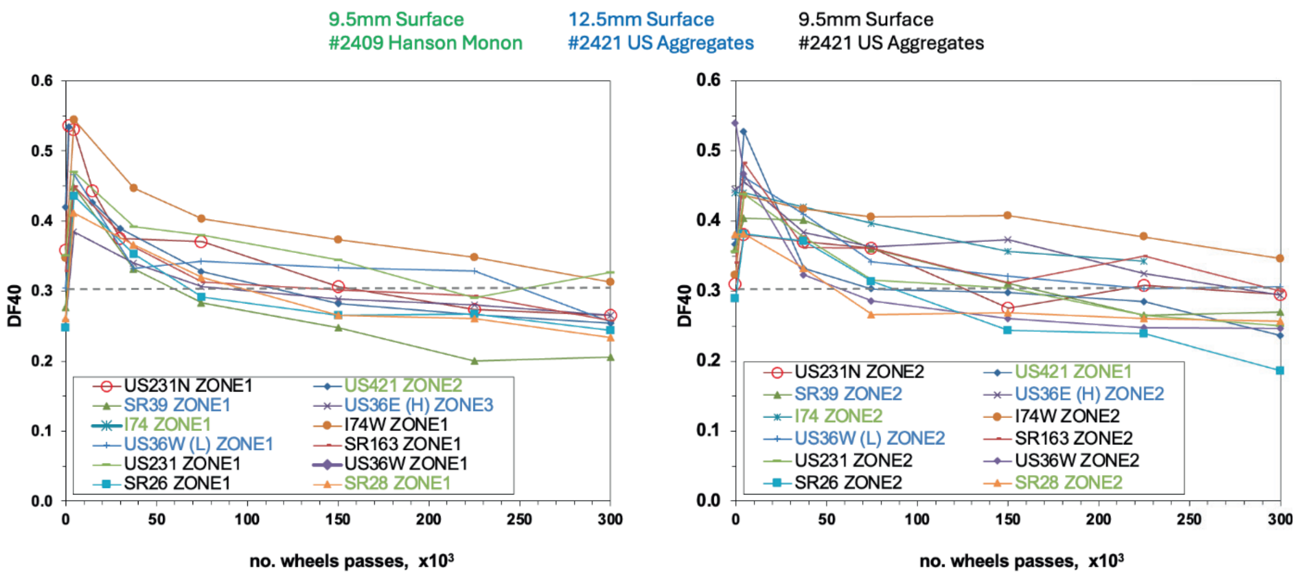


Figure 2.35 Measurement Results of a Typical DFT Test in the Lab.



(a) First Round CTPM Test. (b) Second Round CTPM Test

Figure 2.36 DF40 Measurements From the CTPM Tests.

- Safe pavement friction performance requires DF40 ≥ 0.3, yet only two slabs (from the I-74 WB test zones) retained sufficient wet friction throughout the polishing process. This friction retention is likely due to the incorporation of steel slag, a high-friction aggregate known for its enhanced resistance to polishing.

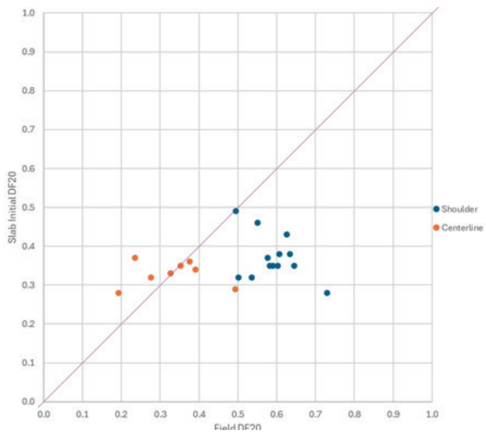
To determine whether the laboratory friction tests reflect field conditions, Figure 2.37 compares field-measured DF20 values with DF20 and DF40 values obtained from slab surfaces:

- Slabs prepared from shoulder samples exhibited lower DF20/DF40 values than the DF20 values measured in the field.
- Slabs prepared from lane center samples showed no significant difference from the corresponding field friction results.

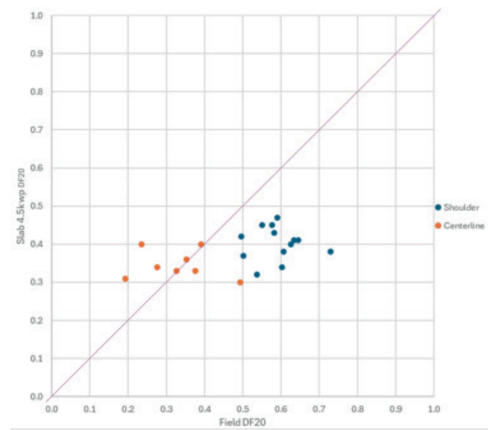
As described in the field evaluation, the IFI) parameters (F60 and S_p) were computed in the laboratory evaluation using CTM-measured MPD and DFT-measured DF40. Figure 2.38 presents F60 values recorded at different polishing stages across the two test rounds. Even though most slabs failed to maintain DF40 ≥ 0.3 after extensive polishing, all slabs maintained sufficient MPD throughout the test. Consequently, all slabs met the minimum F60 criterion of 0.15.

Figure 2.39 compares F60 values from laboratory-prepared slabs with F60 values from their corresponding field pavement surfaces:

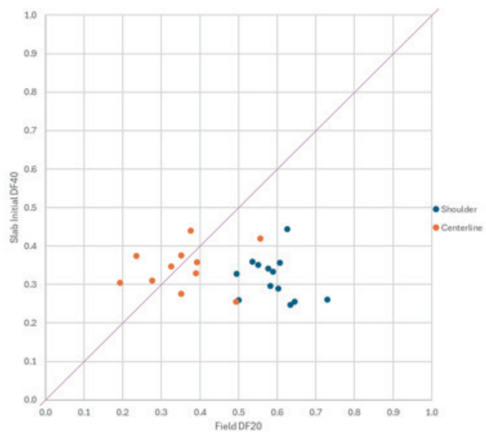
- Field and laboratory results were generally consistent across different test sections.



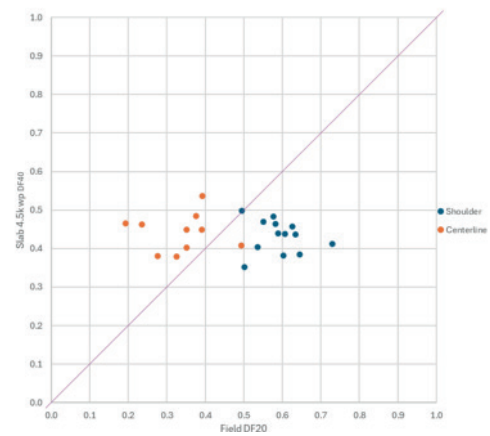
(a) Field DF20 vs. Initial Slab DF20



(b) Field DF20 vs. Slab DF20 After 4.5k wp

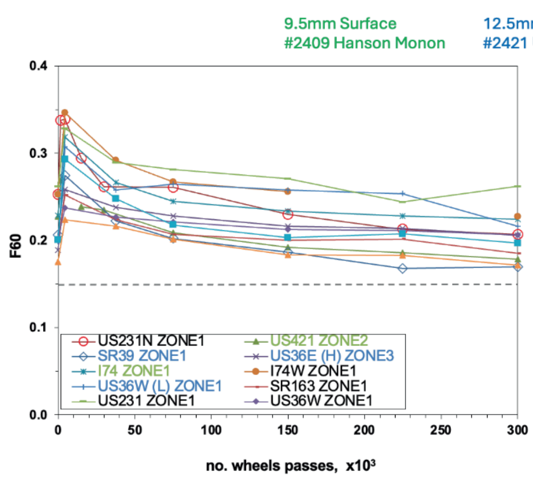


(c) Field DF20 vs. Initial Slab DF40

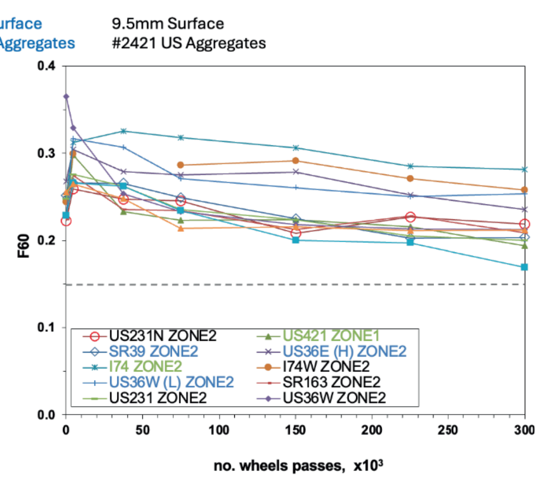


(d) Field DF20 vs. Slab DF40 After 4.5k wp

Figure 2.37 DF Values Measured From the Field Compared With DF Values Measured in the Lab.



(a) First Round CTPM Test



(b) Second Round CTPM Test

Figure 2.38 DF60 Measurements From the CTPM Tests.

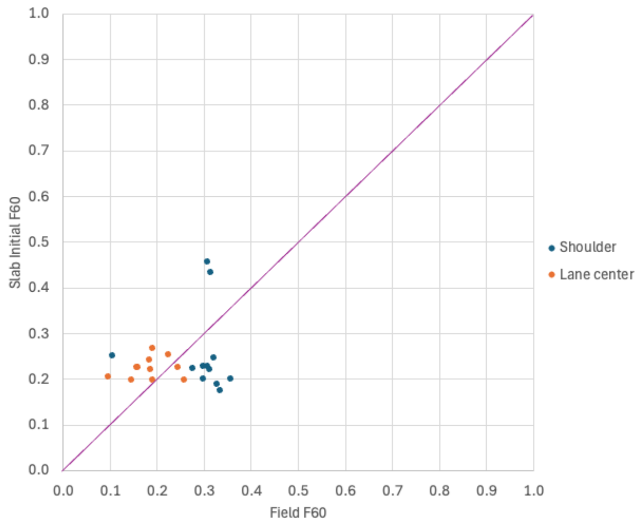


Figure 2.39 Field F60 vs. Slab Initial F60.

- This suggests that the IFI index can serve as a reliable indicator of pavement friction performance in both field and laboratory conditions.

To evaluate the impact of HMA mixture characteristics on friction and texture properties, ANOVA tests were conducted. Table 2.5 summarizes the results:

- DF40 and F60 values significantly decreased with increased polishing cycles, while macrotexture MPD remained stable.
- Mixture size (9.5 mm vs. 12.5 mm HMA) significantly affected DF40, with 9.5 mm mixtures exhibiting higher friction values.
- Aggregate type (D1 vs. D9 dolomite) significantly affected MPD, with D1 mixtures displaying slightly higher macrotexture roughness.

This laboratory evaluation provides critical insights into the relationship between HMA mixture design, texture properties, and long-term pavement friction performance. The key evaluation results include the following:

1. Macrotexture (MPD) remained stable throughout polishing cycles, suggesting that macrotexture deterioration is not a major factor in wet friction loss.

TABLE 2.5
Summary of ANOVA Test Results.

Variable	Factor	Statistical Significance
Macro-MPD	Polishing Stages	Nonsignificant
	Mixture Size	Nonsignificant
	Aggregate Type	Significant
	Traffic Volume	Significant
DF40	Polishing Stages	Significant
	Mixture Size	Significant
	Aggregate Type	Nonsignificant
	Traffic Volume	Significant
F60	Polishing Stages	Significant
	Mixture Size	Nonsignificant
	Aggregate Type	Nonsignificant
	Traffic Volume	Significant

2. Traffic volume (AADTT) had a significant impact on both macrotexture roughness and friction performance.
3. HMA mixture size significantly affected DF40 (with 9.5 mm mixtures exhibiting higher friction), while aggregate type influenced MPD (with D1 mixtures displaying slightly higher roughness).
4. F60 remained above the required minimum throughout the study.

2.4 Summary

This chapter evaluated the macrotexture, microtexture, and friction characteristics of HMA mixtures collected from 14 roadway sections. The analysis focused on the influence of mixture design types and traffic factors on pavement friction performance.

The results of a comparative investigation for 13 different DMFs that included #11 dolomite suggested that the low friction was not closely related to mix designs. The field selection process was conducted using FN40 inventory friction data and DMF information from construction contracts. The selected road sections, located across the Crawfordsville District, incorporated two types of #11 dolomite aggregate sources (D1 and D9) and two surface mixture sizes (9.5 mm and 12.5 mm). To obtain representative test samples, coring was conducted at three designated test zones per roadway section, targeting "unpolished" pavement areas such as shoulders and lane centers. Simultaneously, field friction and texture measurements were performed using the CTM, DFT, and LTS. Since both coring and testing required lane closures and traffic control, they were conducted concurrently to optimize efficiency.

To complement the field study, two rounds of laboratory polishing tests were conducted on 28 HMA mixture slab specimens. The slabs were fabricated from core-extracted surface materials and prepared according to the density and air void specifications outlined in the original pavement DMFs. Each slab underwent 300,000 wheel passes of accelerated polishing using the CTPM. At multiple intervals throughout the polishing process, surface macrotexture and wet friction properties were assessed using CTM and DFT measurements. The collected laboratory data were then analyzed and compared with field test results to identify the underlying causes of low pavement friction observed in certain roadway sections. The main findings are summarized as follows:

- Influence of Aggregate Source of Friction Performance:
  - The aggregate source had a significant impact on macrotexture MPD, though MPD changes at the macro-scale during polishing were relatively minor.
  - Field evaluation results showed that dolomite aggregate sources significantly influenced microtexture parameters, all of which demonstrated a moderate positive correlation with FN40 friction values.
  - Dolomite D1 negatively impacted friction-related microtexture characteristics, contributing to lower pavement friction.
- Effect of Mixture Size on Friction Indices:
  - In field evaluations, mixture size variations did not exhibit a significant effect on DF20 measurements across different lateral locations.
  - However, in laboratory evaluations, slab DF40 values were significantly affected by mixture size, with smaller mixture sizes demonstrating better friction performance.

- The combined IFI parameter F60, which accounts for both macrotexture and microtexture effects, did not exhibit significant variation due to mixture size, suggesting that its influence is less pronounced when macrotexture is factored in.

These findings indicate that aggregate quality of different aggregate sources play a critical role in determining pavement microtexture and long-term friction performance. Additionally, while mixture size does influence short-term frictional resistance, its effect diminishes when evaluated alongside macrotexture parameters.

3. AGGREGATE PROPERTIES EVALUATION AND ANALYSIS

3.1 Introduction

The friction of pavement surfaces is a critical factor in roadway safety, influenced by elements such as mix design, construction techniques, and operational conditions. Aggregates play a fundamental role in pavement composition, accounting for approximately 90% of the total volume in HMA and 80% in portland cement concrete (PCC) pavements (Papagiannakis & Masad, 2008). Beyond their structural contributions, aggregates significantly affect surface texture and friction characteristics. Under real-world traffic and environmental exposure, aggregates undergo polishing and particle degradation over time, leading to a gradual reduction in pavement friction. This deterioration can have substantial implications for the functional performance and safety of roadways.

INDOT (2024) utilizes a variety of aggregates in pavement construction, including limestone, dolomite, and gravel. Additionally, industrial by-products, such as steel slag and air-cooled blast furnace slag, are incorporated into pavement mixtures to improve performance. Dolomite is commonly used in asphalt pavements, particularly for medium-volume roads, while steel slag is often added to mixtures for high-volume roads to enhance durability and friction (West et al., 2001). Previous studies have shown that dolomite offers superior friction compared to limestone (West et al., 2001).

Dolomite is a carbonate rock primarily composed of the mineral dolomite ($CaMg(CO_3)_2$), which is distinguished by its magnesium content. Magnesium enhances the durability of dolomite aggregates, improving resistance to freeze-thaw cycles and reducing susceptibility to polishing (Bao et al., 2024). Some state Departments of Transportation (DOTs) classify dolomite based on a minimum magnesium content requirement. According to INDOT (2024) specifications, dolomite is defined as an aggregate containing at least 10.3% elemental magnesium (equivalent to 17.1% magnesium oxide), corresponding to 78.1% pure dolomite mineral. However, no universally accepted minimum magnesium content standard exists, leading to variations in dolomite classification across different states. Furthermore, scientific research remains limited regarding the precise magnesium content threshold required to define dolomite effectively.

Friction performance is dictated by the interplay of the mechanical, physical, and chemical properties of aggregates (Li et al., 2017; Li et al., 2021).

- Mechanical properties are typically evaluated using:
  - LAA test: Assesses aggregate resistance to fragmentation and wear.
  - MDA test: Evaluates aggregate durability and resistance to abrasion under wet conditions.
  - PSV test: Measures the ability of an aggregate to maintain friction performance after polishing.
- Physical properties such as bulk specific gravity (BSG), water absorption (WA), soundness, and hardness (Mohs scale) determine aggregate stability and long-term performance.
- Chemical properties include elemental composition—such as silicon, aluminum, iron, calcium, magnesium, and titanium—which can influence aggregate durability, hardness, and resistance to polishing.

To ensure that dolomite aggregates provide adequate friction throughout their service life, comprehensive laboratory testing and data analysis are necessary to establish the relationships between their physical, mechanical, and chemical properties. This portion of the study aims to deepen the understanding of the impact of dolomite on pavement friction performance through the following tasks:

- Compare the physical, mechanical, and chemical properties of dolomite with other commonly used aggregates, including limestone, gravel, steel slag, and calcined bauxite, based on laboratory test data.
- Investigate the intrinsic relationships among the physical, mechanical, and chemical properties of dolomite to identify key factors influencing its friction performance.
- Assess the friction performance of aggregates extracted from field cores using the PSV test to evaluate their behavior over the pavement service life.
- Integrate in-field and laboratory data to establish property thresholds for dolomite aggregates, ensuring optimal performance and long-term durability.

3.2 Laboratory Test and Evaluation

This section examines the physical, mechanical, and chemical properties of dolomite sourced from 22 locations across ten different producers. These properties were evaluated using standardized testing methods established by AASHTO and ASTM. Several properties, including the LAA, MDA, BSG, WA, and Soundness, were referenced from a previous study (Bao et al., 2024), while additional tests such as PSV, chemical composition, and hardness were conducted as part of this research. These data were used to analyze the characteristics of dolomite and explore the factors influencing its friction and abrasion resistance. Additionally, PSV values from field-collected aggregates were assessed to investigate potential causes of low-friction roadway segments.

3.2.1 Mechanical Properties

The mechanical properties of aggregates were evaluated using the LAA, MDA, and PSV tests. For LAA testing, aggregate samples (graded 9.5–19.0 mm) were prepared following AASHTO T 96 (AASHTO, 2022c). The MDA test involved aggregate samples (graded 4.75–12.5 mm) prepared in accordance with AASHTO T 327 (AASHTO, 2022b). Table 3.1 presents the specified limits for LAA and MDA. Both tests assess aggregate degradation due to impact, abrasion, and grinding, with the primary difference being that the MDA test is conducted in the presence of water.

- LAA Test: Conducted in a rotating steel drum containing steel balls, subjecting aggregates to impact and abrasion (ASTM, 2010). The percentage loss is determined by measuring the mass retained on a 1.7 mm sieve. Aggregates must be dried before testing.
- MDA Test: Performed with aggregates soaked in water for at least one hour before testing (ASTM, 2017). The soaked samples are placed in a steel tank with water and steel balls, subjected to rotational abrasion. Material loss is determined by measuring the percentage passing through a 1.18 mm sieve.

The PSV test assesses aggregate wear resistance, particularly the frictional properties after polishing. The test consists of two stages:

1. Polishing Stage: Aggregate specimens are polished using the British Wheel Accelerated Polishing Machine.
2. Friction Measurement: The BPT evaluates surface friction after polishing.

TABLE 3.1
Specified Limits for Aggregate Properties.

Property	Limit
LAA (INDOT, 2024)	Max 30–50%[a]
MDA (INDOT, 2024)	Max 18%
PSV10 (Diringer, 1990, as cited in West et al., 2001)	24 or less (Poor Quality) 25 to 30 (Marginal) 30 or more (Good)

[a]The maximum value should not exceed the range of 30–50%, depending on the classification of the aggregate.

Aggregates were prepared following AASHTO T 279 (AASHTO, 2022a), selecting samples sized 6.3–9.5 mm. Figure 3.1 illustrates the graded aggregate samples, and Figure 3.2 displays the sample preparation process.

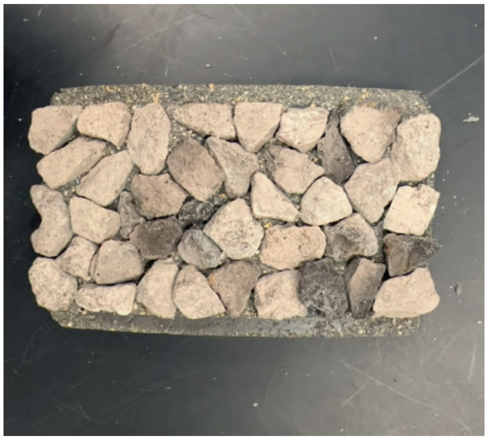
After 10 hr of polishing, friction numbers were recorded using a BPT, as shown in Figure 3.3. The BPT, with a 31.75 mm (1.25 in.) wide slider, records friction values on two scales: the main scale and the F-scale. In this study, friction values were recorded from the main scale. Each coupon underwent multiple measurements, and the final PSV result was determined by averaging the lowest friction values obtained from four consecutive measurements within an acceptable error margin.

Table 3.2 presents the average values for LAA loss, MDA loss, and PSV for 22 dolomite sources. The PSV0 and PSV10 represent the British Pendulum Numbers (BPNs) before and after 10 hr of polishing, respectively, while ΔPSV denotes the difference between these two values, indicating the extent of friction loss due to polishing.

For comparison, the average LAA loss, MDA loss, and PSV values for limestone, gravel, steel slag, and calcined bauxite, derived from previous studies (Bao et al., 2024), are also provided. The following can be observed in the table:

- Under dry conditions, dolomite exhibits a higher average LAA loss compared to other aggregates, indicating greater susceptibility to impact and abrasion.
- In the presence of water, dolomite demonstrates better wear resistance than limestone, suggesting improved durability in wet conditions.
- Friction performance after polishing (PSV10): Dolomite shows lower friction than other aggregates, suggesting a greater tendency for surface polishing over time.
- The average values of LAA, MDA, and PSV10 for dolomite, limestone, gravel, steel slag, and calcined bauxite all meet the standard limits outlined in Table 3.1.
- However, certain dolomite samples exceed the specified standard limits, indicating variability in performance across different sources.

Figure 3.1 Aggregate Samples (Grading 6.3–9.5 mm).



(a) Coupon

(b) Test Coupon Placement

(c) British Wheel Accelerated Polishing Machine

Figure 3.2 British Wheel Accelerated Polishing Machine, Coupon, and Test Coupon Placement.

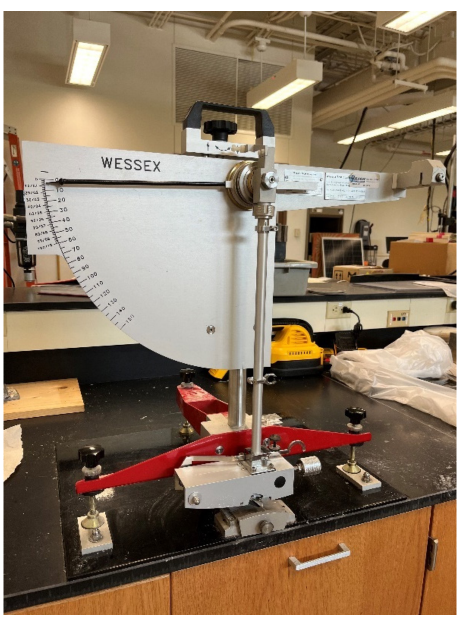


Figure 3.3 British Pendulum Tester.

TABLE 3.2
Mechanical Properties Statistics.

Property	Metrics	Dolomite	Limestone	Gravel	Steel Slag	Calcined Bauxite
LAA (%)	Average	28.06	25.48	22.20	14.28	9.3
	STD	3.68	3.01	4.32	2.60	0.28
	Range	19.88–37.53	-	-	-	-
MDA (%)	Average	11.38	15.28	8.82	6.26	5.23
	STD	2.97	2.77	4.47	1.34	0.06
	Range	5.95–19.7	-	-	-	-
PSV0	Average	42.27	-	-	-	-
	STD	2.57	-	-	-	-
	Range	36.28–46.75	-	-	-	-
PSV10	Average	28.49	30.48	28.88	29.90	35.4
	STD	2.78	2.21	2.67	2.97	0.89
	Range	23.75–33.75	-	-	-	-
ΔPSV	Average	13.78	-	-	-	-
	STD	2.944	-	-	-	-
	Range	7.28–18.88	-	-	-	-

3.2.2 Physical Properties

The physical properties of dolomite were evaluated based on BSG, WA, soundness, and hardness. These properties are crucial for assessing aggregate density, porosity, durability, and resistance to wear and polishing.

- BSG and WA: The BSG and WA of dolomite were determined using the AASHTO T 85 method (AASHTO, 2022e).
  - BSG is an indicator of aggregate density and porosity, calculated as the ratio of the oven-dry weight of the aggregate to its total volume, including permeable voids. A higher BSG signifies a denser aggregate with lower porosity.
  - WA represents the percentage of water absorbed relative to the aggregate's oven-dry weight. A higher WA indicates greater porosity and moisture retention.
- Soundness (Freeze-Thaw Resistance): Soundness was assessed according to AASHTO T 103 (AASHTO, 2022d) by subjecting the aggregates to freeze-thaw cycles. This test measures mass loss due to particle breakdown under extreme temperature fluctuations and moisture exposure.
  - A higher soundness value indicates a greater mass loss, meaning the aggregate is less durable and more susceptible to degradation.
- Hardness (Abrasion and Wear Resistance): The hardness of dolomite was evaluated using the Mohs hardness scale (ASTM, 2020a), which ranks minerals from 1 (softest) to 10 (hardest).
  - Higher hardness values generally correlate with better friction performance and greater resistance to polishing and wear.

Table 3.3 summarizes the physical properties of dolomite and compares them with limestone, gravel, steel slag, and calcined bauxite:

- Density and Porosity: Dolomite has an average BSG of 2.63, which is similar to limestone and gravel but lower than steel slag (3.49).
- Moisture Retention: WA of Dolomite (1.90%) is comparable to limestone (1.91%) but higher than gravel (1.61%) and steel slag (1.37%), indicating greater porosity.
- Durability: Dolomite exhibits an average soundness loss of 2.01%, which is lower than limestone (4.23%), suggesting better freeze-thaw resistance.
- Hardness: Dolomite has a lower hardness (3.14) than gravel (5.50) and steel slag (6.00), making it more prone to polishing and wear over time. However, variability across different dolomite sources indicates differences in material composition and performance.

Based on the measurements of physical properties, the findings are summarized as follows:

- Dolomite exhibits comparable density and porosity to limestone and gravel but higher moisture retention than gravel and steel slag.
- Its freeze-thaw resistance is better than limestone but slightly inferior to gravel and steel slag.
- The relatively low hardness of dolomite suggests it is more susceptible to polishing and wear over time, which may impact its long-term friction performance.
- Variations in hardness and soundness among dolomite sources underscore the importance of careful selection to optimize pavement durability and friction performance.

3.2.3 Chemical Properties

The chemical composition of aggregates plays a crucial role in determining their physical and mechanical properties. In this study, XRF analysis was conducted following ASTM C114 (ASTM, 2022) to assess the elemental composition of aggregates. The chemical components were reported in their oxide forms to facilitate comparison.

Table 3.4 presents the chemical composition statistics for dolomite, limestone, gravel, steel slag, and calcined bauxite. Dolomite is notably characterized by a high magnesium oxide content, averaging 20.36%, which sets it apart from limestone and other aggregate types. Conversely, dolomite exhibits a relatively low silica (SiO_2) content, averaging 3.23%, significantly lower than gravel (40.62%). Additionally, minor oxide components such as aluminum oxide at 0.45% and iron oxide (Fe_2O_3)

TABLE 3.3
Physical Properties Statistics.

Property	Metrics	Dolomite	Limestone	Gravel	Steel Slag	Calcined Bauxite
BSG (%)	Average	2.63	2.61	2.63	3.49	-
	STD	0.08	0.11	0.03	0.18	-
	Range	2.47–2.75	-	-	-	-
WA (%)	Average	1.90	1.91	1.61	1.37	-
	STD	0.84	1.61	0.33	0.52	-
	Range	0.80–4.26	-	-	-	-
Soundness (%)	Average	2.01	4.23	2.02	1.59	-
	STD	1.93	4.58	1.05	1.36	-
	Range	0.38–7.00	-	-	-	-
Mohs (Hardness)	Average	3.14	3.50	5.50	6.00	9.00
	STD	0.36	-	-	-	-
	Range	2.30–3.70	-	-	-	-

TABLE 3.4
Chemical Composition Statistics.

Property	Metrics	Dolomite	Limestone	Gravel	Steel Slag	Calcined Bauxite
SiO_2 (%)	Average	3.23	4.40	40.62	12.52	6.82
	STD	3.44	0.63	13.97	-	-
	Range	0.08–11.75	-	-	-	-
Al_2O_3 (%)	Average	0.45	0.85	4.36	5.71	86.93
	STD	0.36	0.24	1.49	-	-
	Range	0.00–1.16	-	-	-	-
Fe_2O_3 (%)	Average	0.35	0.74	2.59	29.53	1.63
	STD	0.27	0.2	1.11	-	-
	Range	0.08–1.27	-	-	-	-
CaO (%)	Average	29.62	35.35	22.64	38.49	0.36
	STD	1.39	1.64	11.06	-	-
	Range	26.97–33.41	-	-	-	-
MgO (%)	Average	20.36	15.96	5.73	10.22	0.09
	STD	1.42	1.95	2.18	-	-
	Range	15.82–21.71	-	-	-	-
TiO_2 (%)	Average	0.02	0.06	0.26	0.33	3.45
	STD	0.02	0.01	0.15	-	-
	Range	0.00–0.05	-	-	-	-

at 0.35% are also present at lower concentrations compared to steel slag and calcined bauxite.

The observed variation in magnesium oxide (ranging from 15.82–21.71%) and silicon dioxide (ranging from 0.08–11.75%) across different dolomite sources highlights the heterogeneity of the material. Notably, certain dolomite sources fall below the INDOT minimum threshold of 10.3% elemental magnesium (equivalent to 17.08% magnesium oxide; INDOT, 2024). This variability underscores the need for careful aggregate selection to ensure consistent pavement performance.

3.2.4 PSV Test Results of Dolomite

Table 3.5 presents the PSV test results for dolomite obtained from 22 different sources (denoted by D) across ten producers (denoted by P). The initial PSV (PSV0), post-polishing PSV (PSV10), and the difference (ΔPSV) between the two values were recorded. PSV10 values were classified into three performance levels, as outlined in Table 3.1: Poor (PSV10 ≤ 24), Marginal (24 < PSV10 < 30), and Good (PSV10 ≥ 30).

TABLE 3.5
PSV Values of Dolomite.

Producer No.	Source No.	PSV0 (Min, Max)[a]	STD[b] (PSV0)	PSV10 (Min, Max)	STD (PSV10)	ΔPSV	PSV10 Level[c]
P1	D1	36.28 (34.00, 41.00)	2.8	29.00 (27.00, 31.00)	1.4	7.28	Marginal
P1	D2	39.25 (38.00, 40.00)	0.8	23.75 (20.00, 29.00)	3.4	15.50	Poor
P1	D3	41.00 (37.00, 45.00)	3.2	27.33 (24.80, 29.00)	1.8	13.68	Marginal
P1	D4	41.13 (39.00, 43.50)	1.7	28.13 (25.00, 30.00)	1.9	13.00	Marginal
P1	D5	41.25 (40.00, 44.00)	1.6	27.50 (24.00, 31.00)	3.0	13.75	Marginal
P1	D6	41.48 (40.40, 42.50)	0.8	25.50 (24.00, 28.00)	1.5	15.98	Marginal
P1	D7	41.88 (40.00, 46.00)	2.5	30.48 (29.90, 32.00)	0.9	11.40	Good
P1	D8	42.00 (41.00, 43.00)	0.7	30.50 (29.00, 33.00)	1.5	11.50	Good
P2	D9	38.75 (35.00, 40.00)	2.2	25.00 (24.00, 26.00)	0.7	13.75	Marginal
P2	D10	41.75 (38.00, 45.00)	2.6	26.88 (24.50, 30.00)	2.2	14.88	Marginal
P2	D11	45.00 (44.00, 46.00)	1.0	26.75 (25.00, 30.00)	1.9	11.25	Marginal
P3	D12	41.00 (40.00, 42.00)	1.0	29.33 (25.30, 32.50)	2.6	11.68	Marginal
P3	D13	42.00 (40.00, 44.00)	1.6	30.75 (30.00, 32.00)	0.8	11.25	Good
P3	D14	43.88 (42.50, 45.50)	1.4	27.48 (25.00, 30.00)	2.5	16.40	Marginal
P3	D15	45.00 (44.00, 46.00)	0.6	33.13 (29.50, 35.00)	2.1	11.88	Good
P4	D16	43.50 (40.00, 46.00)	2.2	27.95 (24.00, 38.00)	5.8	15.55	Marginal
P5	D17	46.75 (45.00, 48.00)	1.1	31.00 (30.00, 33.00)	1.2	15.75	Good
P6	D18	42.75 (40.00, 44.50)	1.6	33.75 (31.00, 35.00)	1.6	9.00	Good
P7	D19	45.13 (44.00, 47.50)	0.8	27.88 (20.00, 37.00)	6.3	17.25	Marginal
P8	D20	44.00 (40.00, 44.00)	1.6	32.88 (29.50, 35.00)	2.3	11.13	Good
P9	D21	39.68 (39.00, 40.00)	0.4	24.13 (20.00, 36.00)	6.9	15.55	Marginal
P10	D22	46.50 (43.00, 48.00)	2.1	27.63 (25.00, 31.50)	2.8	18.88	Marginal
95% Confidence Interval		(37.58, 46.62)	-	(23.95, 33.42)	-	(8.18, 18.02)	-

[a] (Min, Max): minimum and maximum PSV0 or PSV10 values.
[b] STD: standard deviation.
[c] PSV10 Level: Poor: PSV10 ≤ 24; Marginal: 24 < PSV10 < 30; Good: PSV10 ≥ 30

Among the tested sources, only one (D2 from P1) exhibited poor friction performance after polishing, with a PSV10 of 23.75. All other sources demonstrated either marginal or good performance. Notably, D1 and D9 are of particular interest as they are linked to low-friction road sections. These road segments exhibited a significant decline in friction within 5 years of service, prompting further investigation.

As shown in Table 3.5, although D1 and D9 were categorized at the marginal level in terms of PSV10, their initial PSV values (PSV0) were the lowest and second lowest among all tested aggregates—at 36.28 and 38.75, respectively. Notably, D1 and D9 each included a specimen with relatively high PSV0, even though both groups exhibited the lowest minimum PSV0 values among all tested aggregates. This indicates that the friction performance of D1 and D9 is less consistent. Following polishing, the PSV0 of D1 remained comparable to those of other aggregates, whereas D9 showed a lower PSV10 with reduced variability (standard deviation = 0.7). This suggests that aggregates with lower PSV0 values may be more prone to rapid friction loss over time, reinforcing the importance of initial friction in predicting long-term pavement performance.

To further investigate whether the friction performance of aggregates D1 and D9 significantly differed from that of other sources, one-sample t-tests were performed. The results are presented in Table 3.6. Both D1 and D9 exhibited statistically significant differences in PSV0 compared to the mean of the remaining dolomitic aggregates ($p < 0.0001$). However, for polished PSV (PSV10), no significant difference was observed for D1 ($p = 0.5685$), while D9 remained significantly different from the other sources ($p < 0.0001$).

The measured PSV values indicate the following findings:

- The majority of dolomite sources exhibited marginal or good PSV10 values, indicating adequate friction performance after polishing.
- The D2 source from P1 was the only aggregate classified as poor, with a PSV10 of 23.75, making it unsuitable for high-friction applications.
- D1 and D9, associated with low-friction road sections, had the lowest PSV0 values (36.28 and 38.75, respectively) and the lowest minimum PSV0 values (34.00 and 35.00, respectively). One-sample t-tests indicated that PSV0 of D1 and D9 differed significantly from those of other dolomitic aggregates, underscoring that initial friction performance plays a critical role in long-term friction.
- ΔPSV values varied widely, with some sources experiencing significant reductions in friction after polishing. This suggests that initial high PSV values do not always guarantee long-term friction durability.
- Aggregates with a PSV10 above 30 performed well and retained sufficient friction after polishing, making them suitable candidates for durable high-friction pavement surfaces.

TABLE 3.6
T-Test Results for PSV Values of D1 and D9 Compared to Other Aggregates.

Aggregate	PSV type	Null Hypothesis (H_0)	T-Statistic	P-Value	Significant ($p < 0.05$)
D1	PSV_0	$\mu_{D1}=\mu_{others}$	13.56	<0.0001	Yes
D1	PSV_{10}	$\mu_{D1}=\mu_{others}$	-0.58	0.5685	No
D9	PSV_0	$\mu_{D9}=\mu_{others}$	8.38	<0.0001	Yes
D9	PSV_{10}	$\mu_{D9}=\mu_{others}$	5.81	<0.0001	Yes

These results highlight the importance of selecting dolomite sources based on both initial PSV0 and post-polishing PSV10 values to ensure sustained pavement friction.

3.3 Texture Analysis of Dolomite Aggregate

3.3.1 Experiment Design

Aggregate texture properties play a crucial role in the friction performance of asphalt mixtures containing specific aggregate sources. The PSV test is a widely recognized laboratory method for quantifying an aggregate's resistance to traffic-induced polishing. However, conventional texture measurement techniques, such as the CTM and LTS, are limited in their ability to measure the curved surfaces of PSV test specimens accurately. To address this limitation, a non-contact close-range photogrammetry method utilizing the Structure-from-Motion (SfM) technique is proposed for precise 3D surface reconstruction and measurement of PSV specimens.

A low-cost micro-four-thirds camera with a 30 mm macro lens and an integrated macro lighting tool was used to capture images of PSV specimen surfaces before and after the 10-hr polishing process. A 1-in.-thick crafting foam disc with an 87 mm × 56 mm rectangular hole was designed to hold the PSV specimen securely for image acquisition and georeferencing. To further enhance accuracy and ensure consistent camera positioning during 3D reconstruction, a control frame (Figure 3.4) was attached to the foam disc to automate camera calibration and georeferencing.

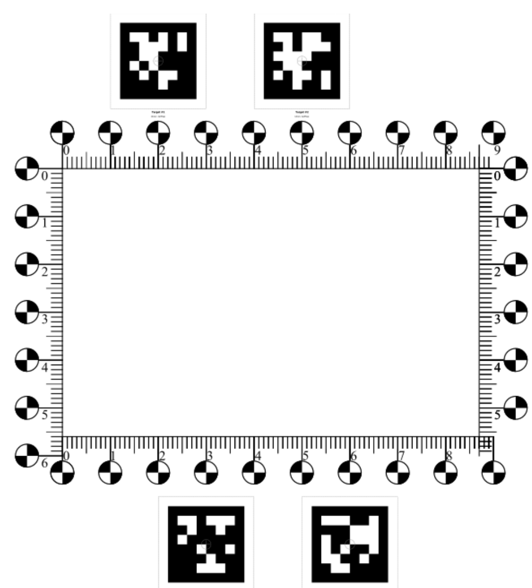
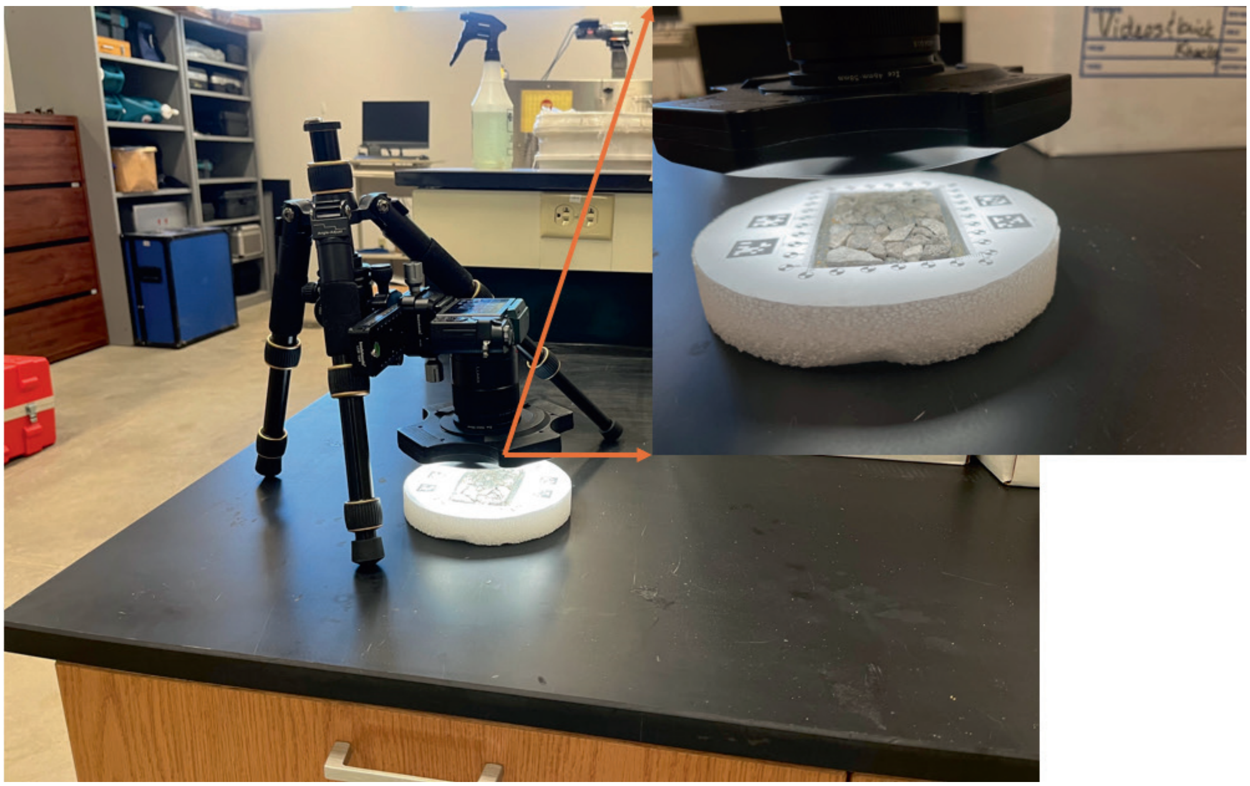


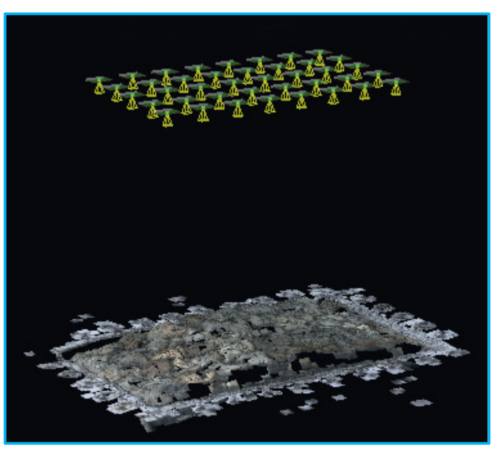
Figure 3.4 Referencing Control Frame for Precise Camera Calibration.

The camera was mounted on a tripod with a 180 mm rail nodal slider, allowing consistent image overlap of 10 mm in both movement directions. Each image acquisition process involved capturing 40 high-resolution images (4592×3448 pixels) following a Cartesian imaging approach to achieve a ground sampling distance of 0.01 mm. Additionally, eight auxiliary images were taken at greater object distances to capture the four fiducial markers for automated georeferencing. Figure 3.5 shows the photogrammetric texture survey setup. The photogrammetric and 3D reconstruction process involved:

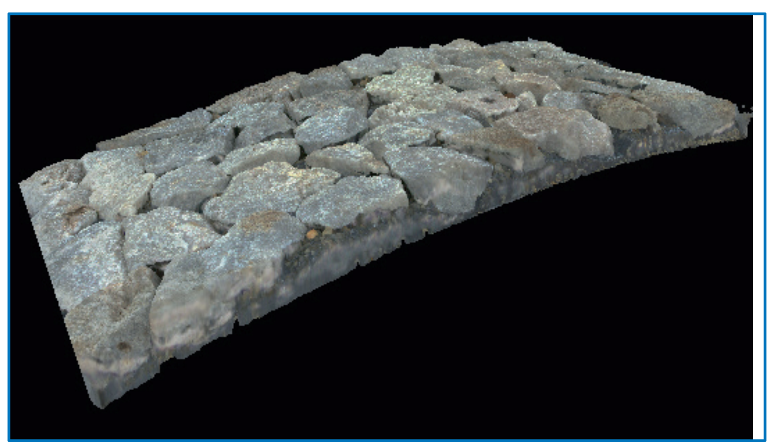
- Aerotriangulation and camera positioning for precise alignment (Figure 3.5a)
- Multi-View Stereo point cloud densification to create a highly detailed surface texture model (Figure 3.5b and Figure 3.5c)



(a) Apparatus



(b) Aerotriangulation Result



(c) Final 3D Texture Model

Figure 3.5 Photogrammetric Texture Survey Setup.

This experimental setup builds upon a previous study on photogrammetric texture measurement of pavement surfaces (Peng, 2024).

3.3.2 3D Surface Analysis of PSV Specimens

The proposed close-range photogrammetry method was applied to scan 22 PSV specimens before and after the 10-hr polishing test. These specimens represented 22 different dolomite aggregate types, covering a wide range of aggregate surface texture properties. Simultaneously, PSV0 and PSV10 values were collected using the BPT to correlate initial and postpolishing surfaces with friction performance.

Figure 3.6 illustrates two representative 3D reconstructions of test specimens, showing both the initial and polished surfaces. While the size, shape, and arrangement of individual aggregate particles varied between specimens, the differences in color and texture between dolomite sources were apparent.

3.3.3 Texture Evolution During Polishing

The height variation in individual aggregate particles during polishing was examined using 3D models. Figure 3.7 presents an example of a single #2421 dolomite particle before and after the PSV test. The polished surface exhibits a noticeable reduction in height variation, confirming the progressive smoothing effect of the polishing process. The sand grains protruding from the initial surface were removed during polishing, leaving small cavities in the final polished surface.

3.3.4 Multiscale Texture Roughness Analysis

A visual inspection of 3D models provides limited insights into surface texture properties. Therefore, multiscale statistical texture parameters were computed to better understand the role of texture roughness in aggregate friction performance. Before conducting quantitative texture analysis, all 3D surface profiles were leveled using polynomial surface fitting to remove the natural curvature of PSV specimens. Figure 3.8 illustrates this leveling process, ensuring that texture characterization was based purely on surface roughness and not influenced by specimen curvature.

Since the initial and polished surfaces of each test specimen are not independent, the two side edges of each specimen were set to zero in height measurements to ensure consistency. Figure 3.9 demonstrates the height-aligned modeling results, where a 2D profile in the rubber sliding direction was sampled to show height variations before and after PSV polishing. In this example from aggregate #2409, the peak heights of individual particles were reduced after polishing. However, narrow edges between consecutive aggregate particles showed a slight increase in height. This is attributed to residual silicon carbide grit accumulating in surface cracks during polishing.

3.3.5 3D Texture Parameters for Friction Analysis

Table 3.7 provides a comprehensive summary of key aggregate properties, detailing their significance, how they are measured, and the implications of higher or lower values on

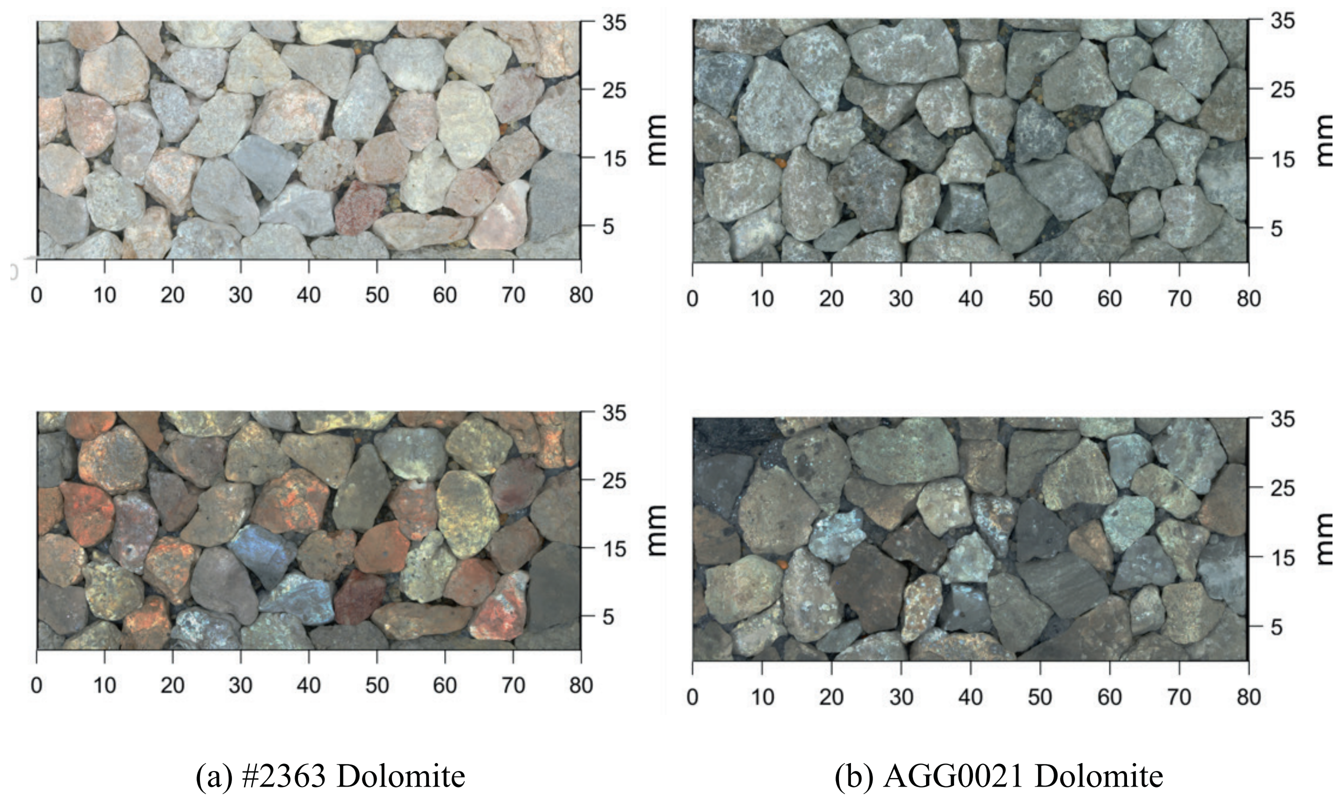


Figure 3.6 Textured 3D Models of Initial (Top) and Polished (Bottom) PSV Specimens.

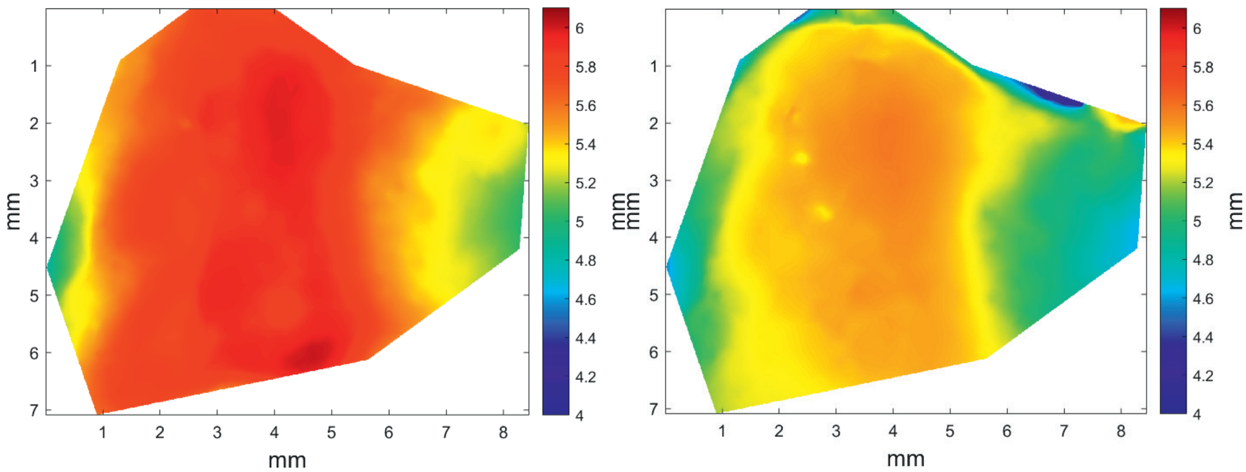


Figure 3.7 Height Variation in a Single #2421 Dolomite Particle Before and After Polishing.

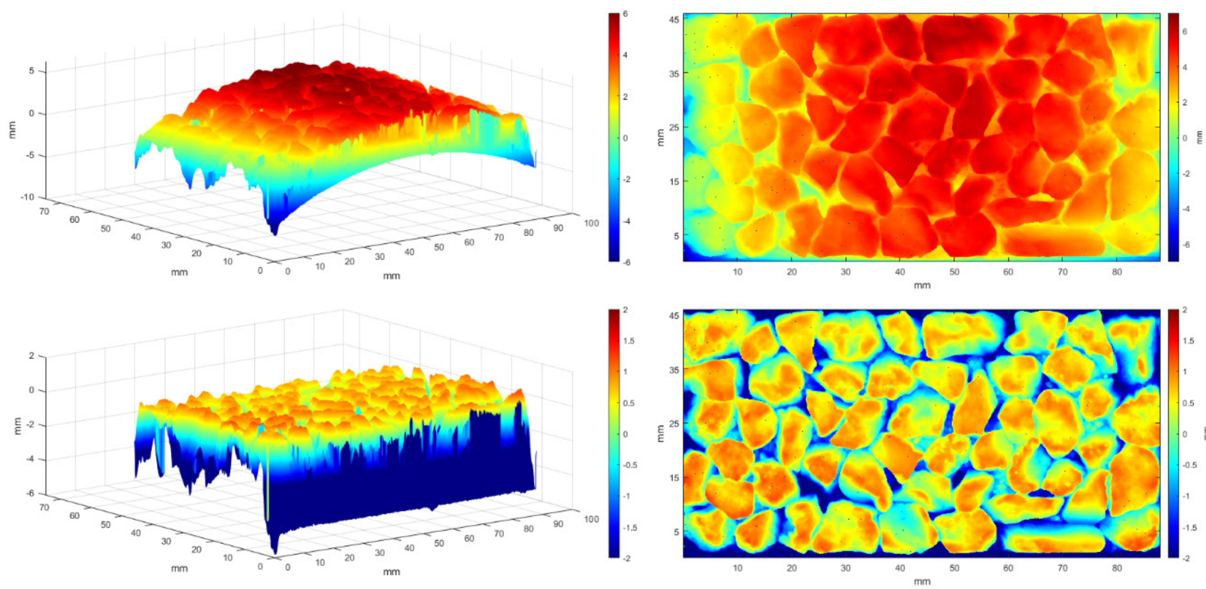


Figure 3.8 Surface Leveling Procedure for Texture Analysis.

pavement performance. These properties were used as part of the 3D texture parameters in the friction analysis.

The MPD standard typically used in pavement texture analysis was not applicable for PSV specimens, as MPD calculation requires a 100 mm baseline of pavement texture profiles, which is not feasible for PSV test specimens. Instead, a set of 3D areal parameters, adapted from the ISO 25178-3 standard (International Organization for Standardization [ISO], 2012), were utilized to investigate the relationship between dolomite aggregate texture and friction. The following 3D texture parameters were computed:

- Height-related parameters: Arithmetic mean height (Sa), RMS height (Sq), Minimum peak height (Sp), Maximum pit height (Sv), Maximum height (Sz), Skewness (Ssk), Kurtosis (Sku)
- Gradient-related parameters: Root mean square gradient (Sdq), Developed interfacial area ratio (Sdr)

While Sa measures the mean absolute height, Sq represents the root mean square height. Sp and Sv denote the absolute height of the largest peak and the deepest pit, respectively, while Sz is the sum of Sp and Sv. Ssk evaluates the degree of bias in the roughness shape, and Sku measures the sharpness of surface roughness. Sdq represents the root mean square slope, and Sdr quantifies the ratio of the developed surface area to the projected plane area. Height parameters primarily describe surface roughness, while gradient parameters offer insights into microtexture characteristics that influence friction. These multiscale 3D texture parameters provide a comprehensive framework for assessing dolomite aggregate friction performance and its resistance to traffic-induced polishing.

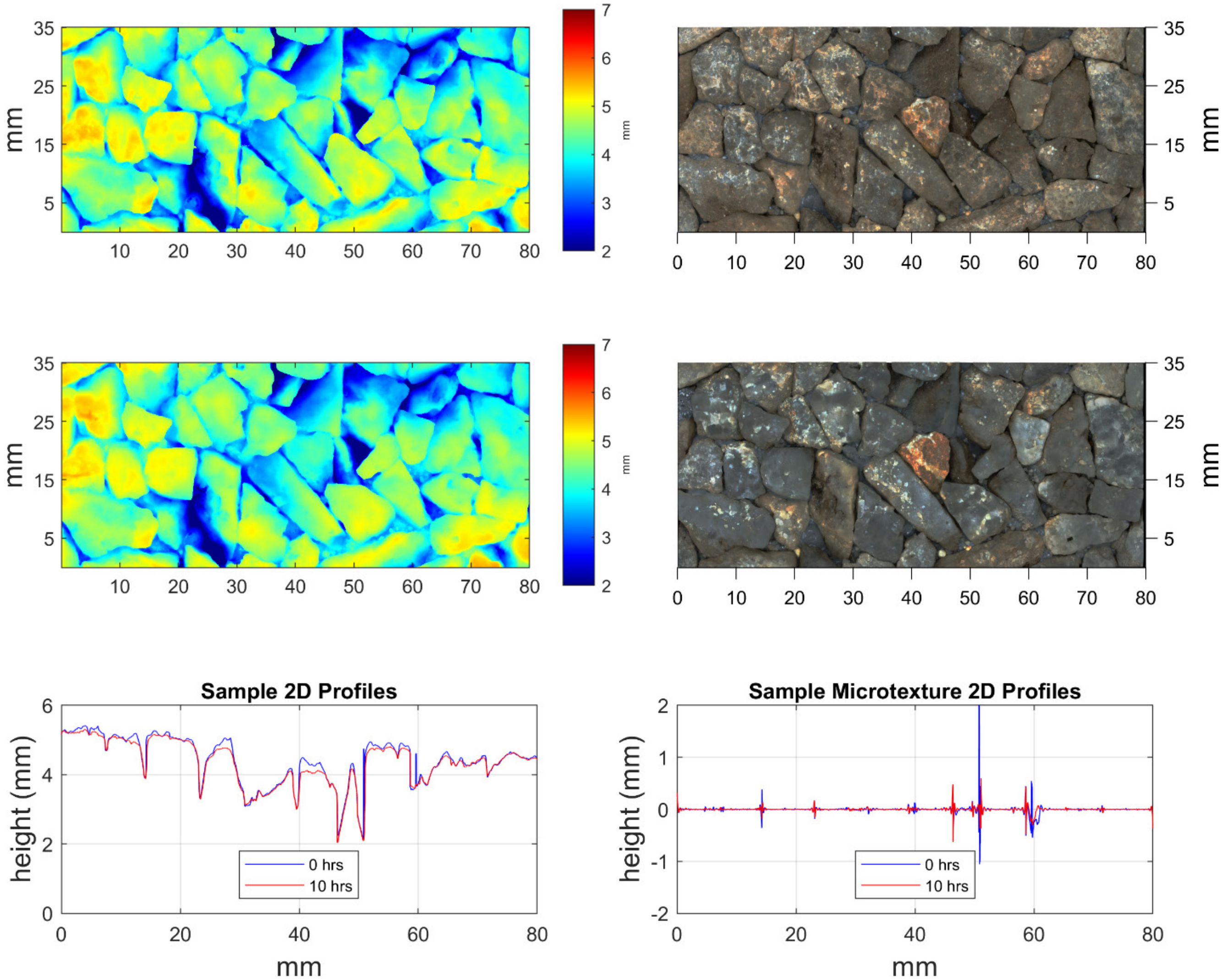


Figure 3.9 Height Heatmap and 3D Models of Flattened Initial and Polished Surfaces as Well as Sample 2D Profile.

TABLE 3.7
Aggregate Parameters Relevant to Friction Analysis.

Parameter	What it Measures	Higher Value Means	Lower Value Means
MDA (%)	Abrasion resistance in wet conditions	More wear in wet conditions (less durable)	More durable in wet conditions
BSG	Density of aggregate	Denser, less porous aggregate (stronger, less moisture absorption)	More porous, absorbs more water
WA (%)	Porosity & ability to retain moisture	More porous, retains more water (less durable)	Less porous, repels moisture (more durable)
LAA (%)	Impact & wear resistance	Weaker, breaks down faster (less wear-resistant)	Stronger, more wear-resistant
Soundness (%)	Freeze-thaw & weathering resistance	More susceptible to weathering (shorter lifespan in harsh climates)	More durable in extreme conditions
PSV0	Friction performance before polishing	Higher initial friction (good traction when new)	Lower initial friction (slippery when new)
PSV10	Friction performance after polishing	Better long-term friction durability (resists polishing & maintains grip over time)	Significant loss of friction over time (becomes more slippery)
Hardness (Mohs Scale)	Resistance to scratching & deformation	More resistant to wear & polishing (stronger aggregate)	Softer, more prone to polishing & wear
MPD	Macrotexture depth of surface	More surface roughness (better drainage & high-speed friction)	Smoother surface (potential hydroplaning at high speeds)

3.3.6 Feature Relevancy Analysis via ANOVA

To identify the most relevant roughness parameters and determine their optimal evaluation scale, an ANOVA was conducted. This analysis examined how the polishing process and aggregate type influenced each roughness parameter. The general implementation follows the linear model:

$$p_i(\lambda,k,n) = \alpha_o + \sum \alpha_{j,k_j}(i,\lambda) + \xi_{k_j,n}(i,\lambda)$$

Equation 3.1

Where:

- $p_i(\lambda,k,n)$ is the i^{th} parameter value of the n^{th} 3D profile taken at polishing level k (k denotes the initial surface, or post 10-hr PSV polishing), calculated at an evaluation scale λ (macrotexture or microtexture).
- α_{j,k_j} represents the main effects of the k-th process parameter level on the i-th parameter value at scale λ.
- $\xi_{k_1,k_2,n}(i,\lambda)$ is Gaussian noise with a zero mean and standard deviation.

For each evaluation scale (macrotexture or microtexture), the ratio of between-group and within-group variability was computed for each polishing stage and aggregate type. The result, denoted as F(p_i, λ), quantifies the relevancy of a roughness parameter at a given evaluation scale (van Gorp et al., 2010).

A higher F-value indicates that the roughness parameter better represents the effects of polishing or the influence of aggregate type. Figure 3.10 presents the F-value distributions for nine different roughness parameters, comparing their effectiveness in capturing polishing effects and aggregate variability.

Through the ANOVA analysis, the following are the key findings:

1. Sdr at both macrotexture and microtexture scales emerged as the most relevant parameter for distinguishing different aggregate types.
2. Sv and Sz at the macrotexture scale were identified as the most sensitive parameters to changes caused by the PSV polishing process.
3. Ssk and Sku were less relevant across both scales compared to other roughness parameters.
4. The relevance of evaluation scales varies by parameter type. Sdr is more sensitive at the macrotexture scale for capturing polishing-induced changes.

Since Sdr was identified as the most relevant roughness parameter, Figure 3.11 presents its variance across different

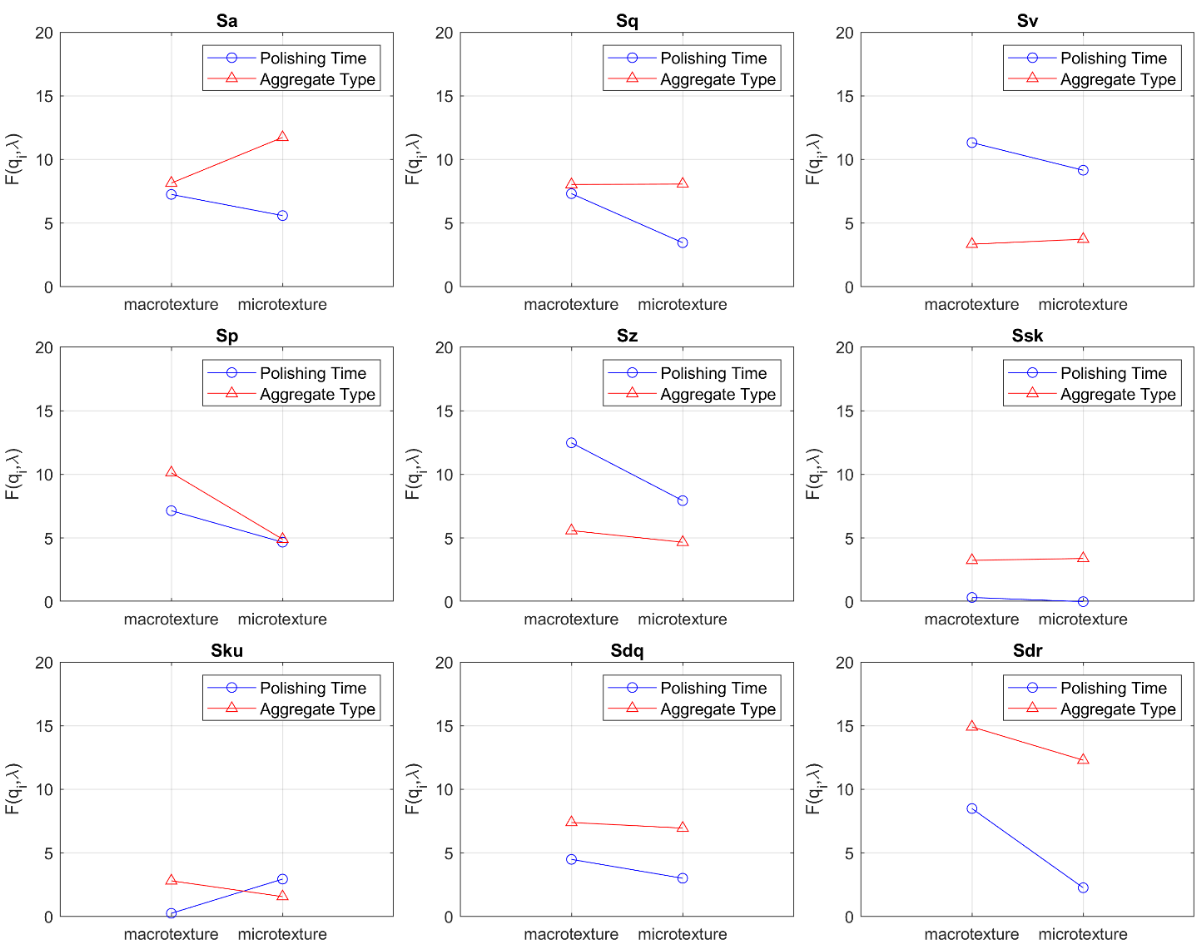


Figure 3.10 Relevancy Criterion F for Nine Roughness Parameters.

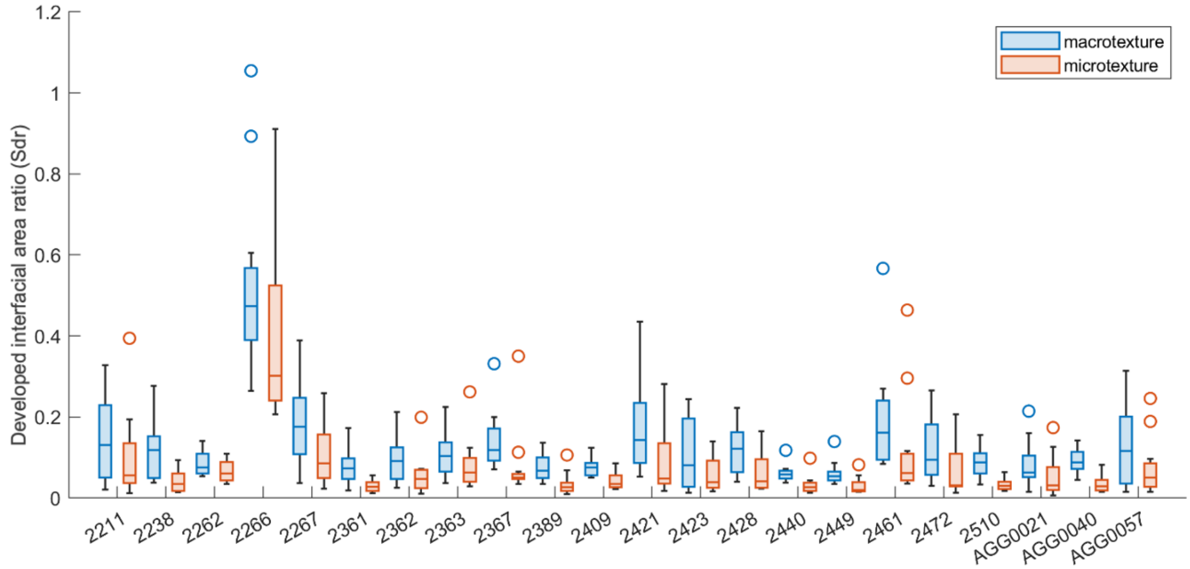


Figure 3.11 Boxplot of Macro- and Microtexture Sdr Variance by Dolomite Source Type.

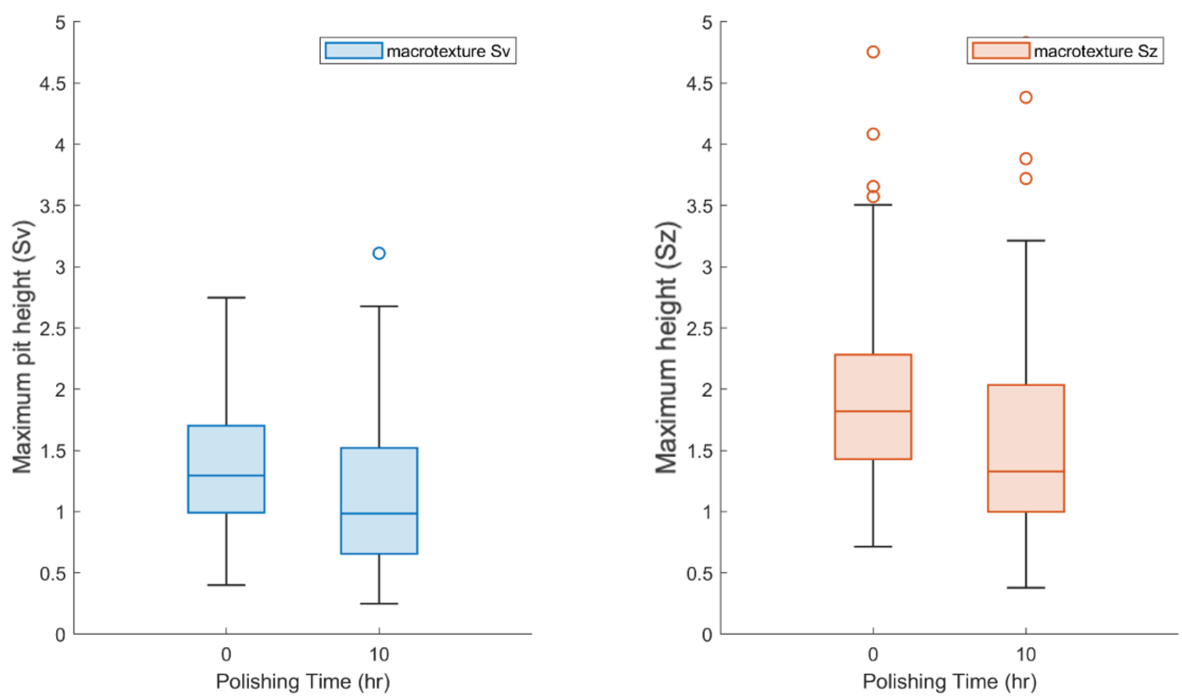


Figure 3.12 Boxplot of Macrotexture Sv and Macrotexture Sz Variance by Polishing Time.

dolomite sources. The boxplots indicate that dolomite #2266 exhibited the highest Sdr values at both macrotexture and microtexture scales, followed by #2267 and #2461. The elevated Sdr values for dolomite #2266 suggest that it retained a rougher texture even after polishing, which may enhance its friction performance.

Figure 3.12 presents the distributions of Sv and Sz before and after polishing. At the macrotexture scale, both parameters were significantly higher on initial surfaces, confirming that the polishing process effectively reduces aggregate peak heights. This aligns with the expectation that surface roughness diminishes over time due to traffic wear, potentially leading to a decline in pavement friction performance.

It is essential to note that the relevance of a roughness parameter in distinguishing aggregate types and polishing effects only provides an indication of texture variability among individual particles. However, the PSV specimens' overall surface texture is also influenced by:

- Particle arrangement within the PSV specimen.
- Variability in aggregate selection during specimen preparation.

Thus, to comprehensively analyze friction performance of dolomite, it is critical to correlate the BPN friction results with the surface texture properties of the entire PSV specimen. This approach will provide a more holistic understanding of how dolomite aggregate texture impacts friction in real-world conditions.

3.3.7 Texture and Friction Performance

A linear correlation analysis was conducted to determine whether a relationship exists between the texture characteristics of PSV specimens and their friction performance, regardless of the polishing stage. The detailed Pearson correlation coefficients are presented in Figure 3.13. The Sdr at both macrotexture and microtexture scales exhibited moderate linear correlations of 0.44 and 0.27, respectively, with PSV friction values. This indicates that Sdr is not only a relevant parameter for distinguishing different dolomite sources but also serves as a useful indicator of the friction performance of an aggregate.

On the other hand, surface microscale Ssk and Sku were found to be moderately negatively correlated with PSV values (-0.36 and -0.32, respectively). Previous studies in surface tribology suggest that higher kurtosis and positive skewness values are associated with reduced friction coefficients (Sedlaček et al., 2017; Tayebi & Polycarpou, 2004). However, since all dolomite sources investigated in this study had negative microscale skewness and large microscale kurtosis (Sku > 3) across both polishing stages, the observed strong correlation does not effectively differentiate the friction performance of the 22 dolomite types or the effects of the polishing process.

In the previous section, macroscale Sv and Sz of individual aggregate particles were observed to decrease after 10 hr of PSV polishing. However, the overall correlation analysis did not reveal a significant linear relationship between PSV values and macroscale Sv or Sz. This is likely because PSV specimens are initially composed of freshly crushed aggregate particles, making their macroscale Sv and Sz highly variable before

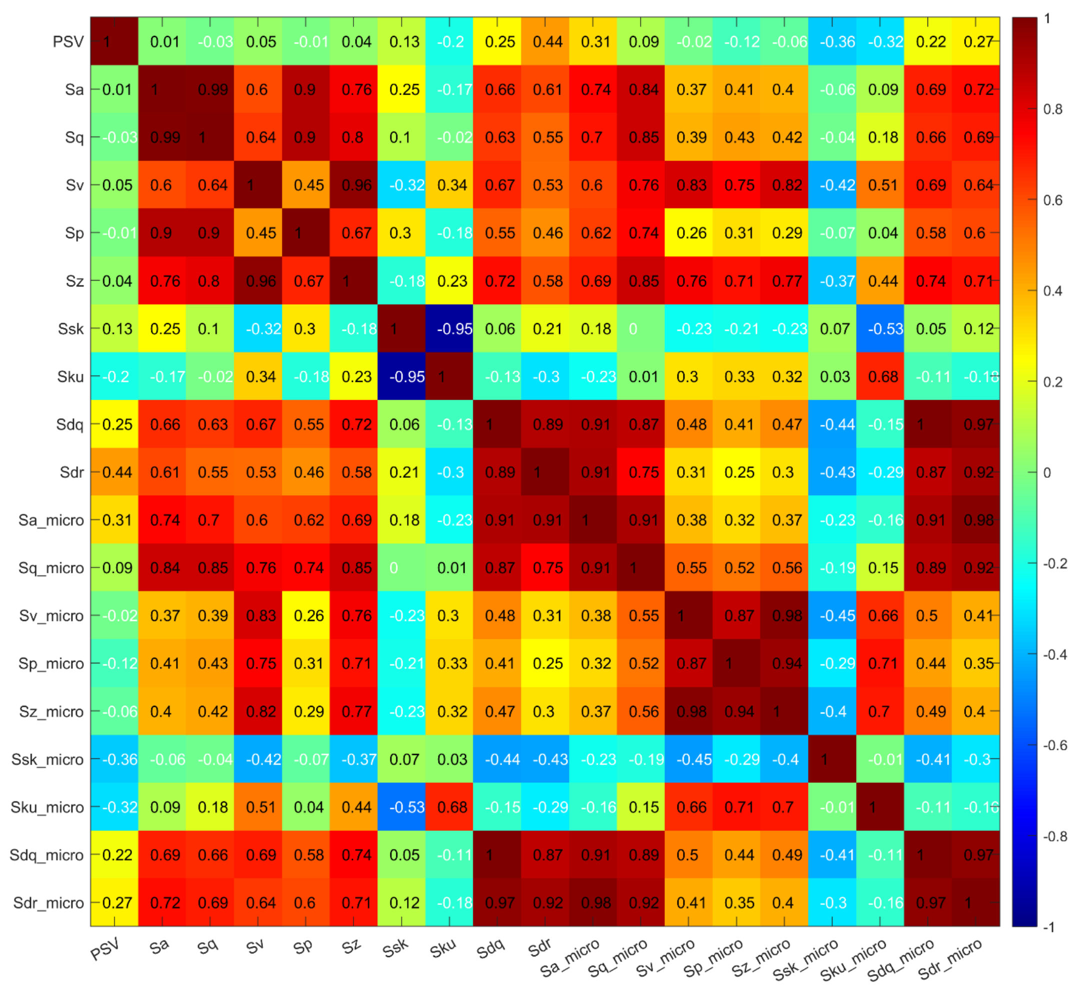


Figure 3.13 Overall Pearson Linear Correlation Analysis Results Between PSV and Specimen Surface Roughness Parameters, Regardless of Polishing Stages.

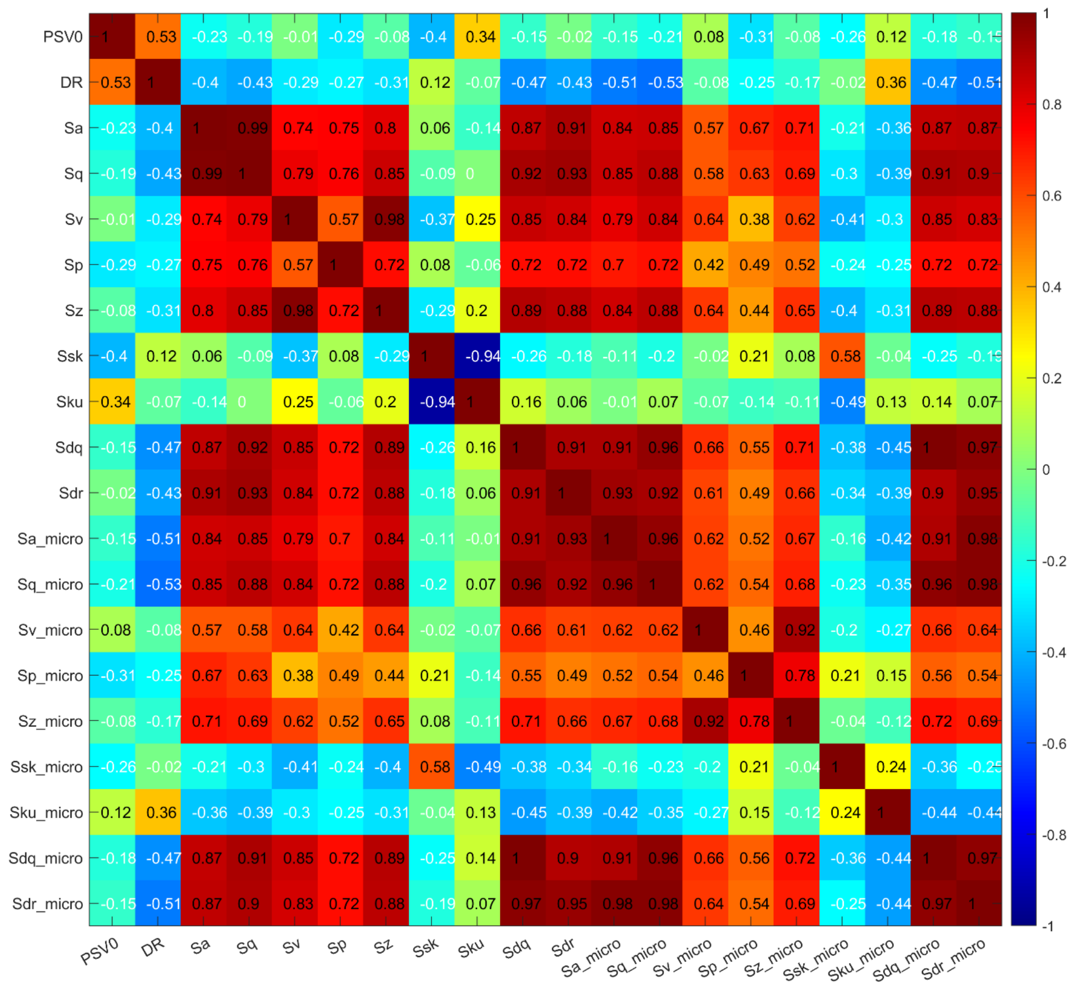


Figure 3.14 Pearson Linear Correlation Analysis Results Between PSV0, DR, and Initial Surface Roughness Parameters.

polishing. Due to the physical nature of these parameters, they are expected to be more robust and friction-relevant after the polishing process.

Figure 3.14 and Figure 3.15 compare PSV0, PSV10, and the friction decreasing rate (DR) with corresponding texture properties. Key findings from these figures include:

- Most texture properties calculated from initial specimen surfaces exhibit weak correlations with PSV0, except for macroscale kurtosis. However, initial macroscale Sku is highly influenced by the arbitrary arrangement of aggregate particles in individual specimens, making it less reliable for assessing differences between dolomite sources.
- In contrast to PSV0, the PSV10 exhibits strong correlations with many roughness parameters at both macrotexture and microtexture scales. Macroscale and microscale Sdr, which were previously identified as the most relevant parameters for differentiating aggregate types, showed Pearson correlation coefficients of 0.45 and 0.51, respectively, with PSV10.
- The macroscale peak height parameters Sv and Sz of the polished surfaces are strongly correlated with PSV10. This suggests that the retention of large peak heights on polished aggregate surfaces is indicative of superior ultimate friction performance.
- Although roughness parameters from initial specimen surfaces show limited correlation with PSV0, they remain useful for predicting the friction decreasing rate. Parameters that exhibit strong negative linear correlations with friction loss on the initial surface continue to maintain this relationship after polishing.

The Sdr was found to be relevant for distinguishing different aggregate sources and was positively correlated with PSV values. This hybrid roughness parameter is calculated using the following equation:

$$Sdr = \frac{1}{A}\left[\iint\left(\sqrt{\left[1+\left(\frac{\partial z(x,y)}{\partial x}\right)^2+\left(\frac{\partial z(x,y)}{\partial y}\right)^2\right]}-1\right)dxdy\right]$$

Equation 3.2

Sdr quantifies the increase in surface area due to roughness. As Sdr increases, the surface becomes more textured and rougher, which can contribute to enhanced friction performance. When comparing the macroscale and microscale Sdr values of the 22 PSV test specimens, the specimen made from

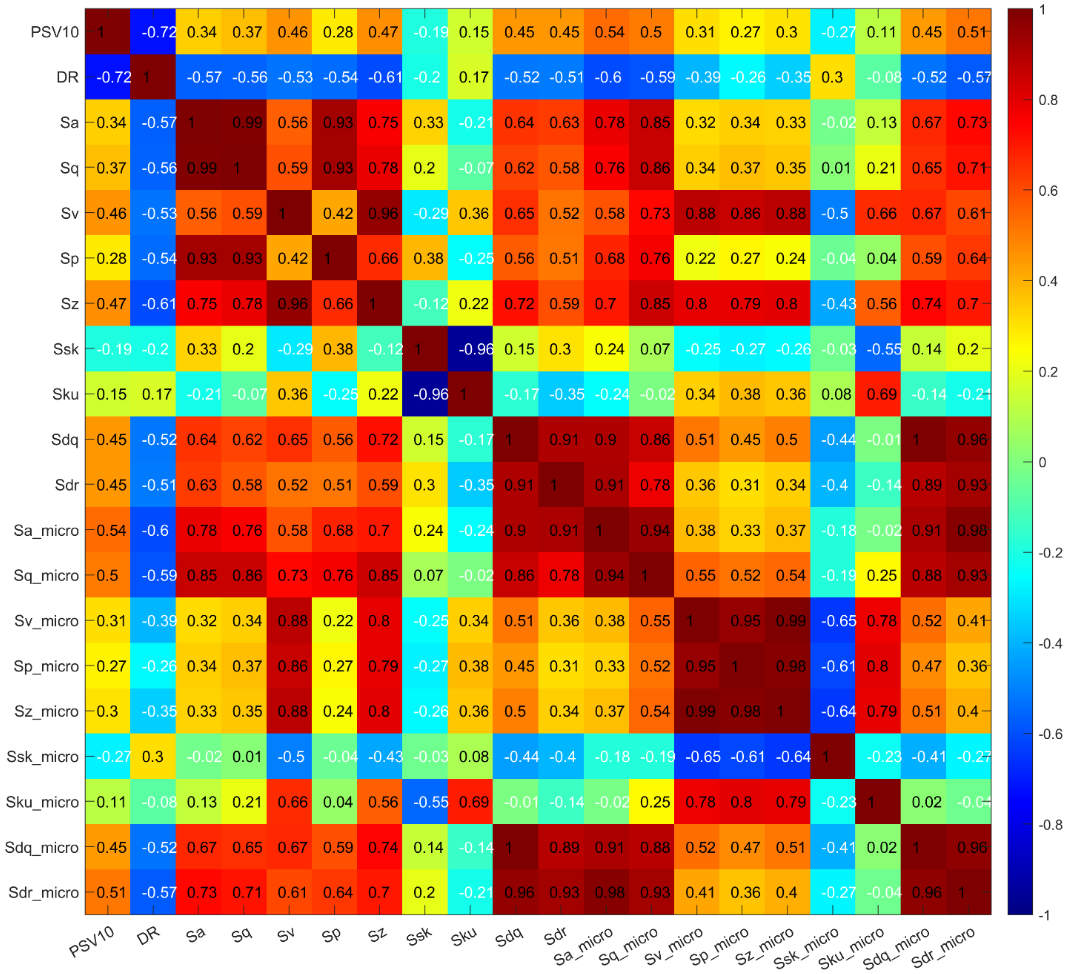


Figure 3.15 Pearson linear correlation analysis results between PSV10, DR, and Polished Surface Roughness Parameters.

the aggregate source #2421 exhibited relatively high Sdr values at both polishing stages (Figure 3.16). This suggests that dolomite #2421 has a relatively low friction loss over time. However, its low initial friction performance (PSV0) remains a concern, as the initial texture properties of the aggregate do not strongly correlate with PSV0.

A similar trend can be observed when analyzing the variations in macroscale Sv and Sz values from polished surfaces. As shown in Figure 3.17, the specimen made from dolomite #2421 exhibited the highest macroscale Sv and Sz values among the 22 tested specimens after the polishing process. This indicates that aggregates from this source retain significant surface roughness post-polishing, which may contribute to their relatively high PSV10 values.

3.4 Correlation Analysis

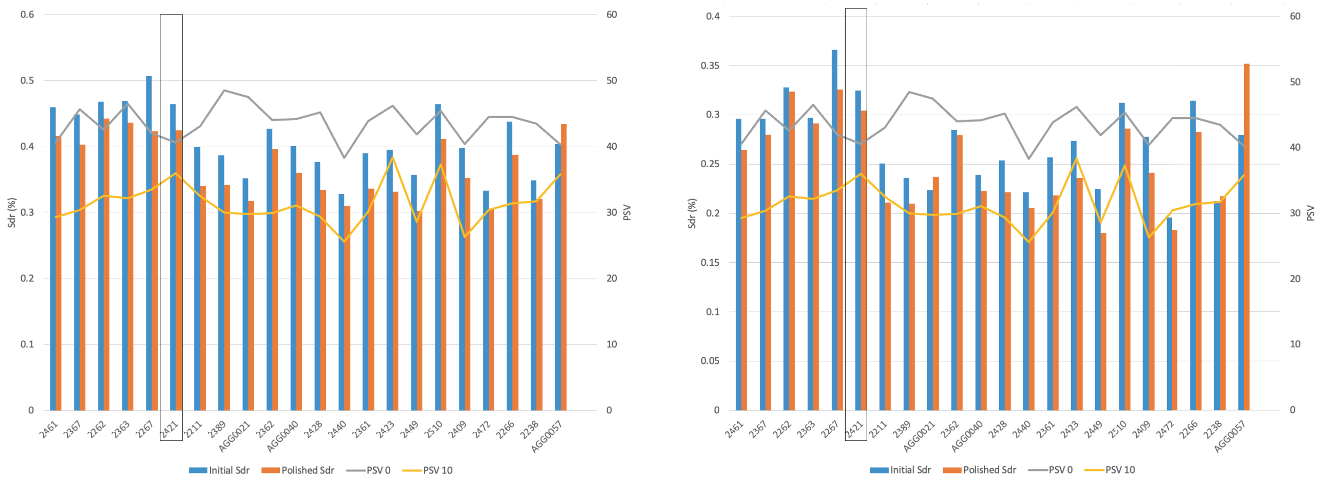
To further explore the influence of various properties on the friction performance of dolomite, a correlation analysis was conducted to examine the relationships between mechanical, physical, and chemical characteristics. In this study, correlation strength was categorized as follows:

- High correlation: Coefficient ≥ 0.6
- Medium correlation: Coefficient between 0.3 and 0.6
- Low correlation: Coefficient between 0 and 0.3

3.4.1 Correlation Analysis of Mechanical and Physical Properties

Figure 3.18 presents a correlation heatmap that illustrates the relationships between the mechanical and physical properties of dolomite. Among the physical properties, WA and BSG exhibit a strong negative correlation (-0.93), indicating that denser dolomite contains fewer voids, whereas less dense dolomite is more porous. Additionally, BSG, WA, and hardness show moderate correlations with soundness loss (-0.34, 0.53, and -0.38, respectively), suggesting that denser and harder dolomite tends to have lower soundness loss and greater resistance to weathering and degradation. In contrast, dolomites with higher WA values are more susceptible to weathering due to their increased porosity, making them more prone to material loss over time.

Further analysis highlights strong correlations between MDA and BSG (-0.83), WA (0.9), and soundness (0.82). The negative correlation between MDA and BSG suggests that denser



(a) Macroscale Sdr

(b) Microscale Sdr

Figure 3.16 Sdr Variation With PSV Performance for 22 Test Specimens.

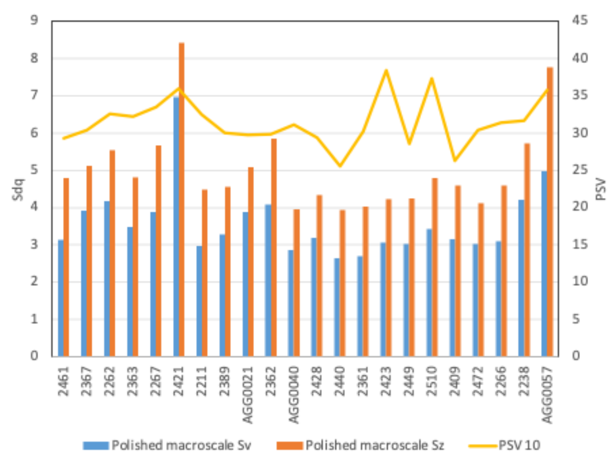


Figure 3.17 Polished Macroscale Sv and Sz Variation with PSV Performance for 22 Test Specimens.

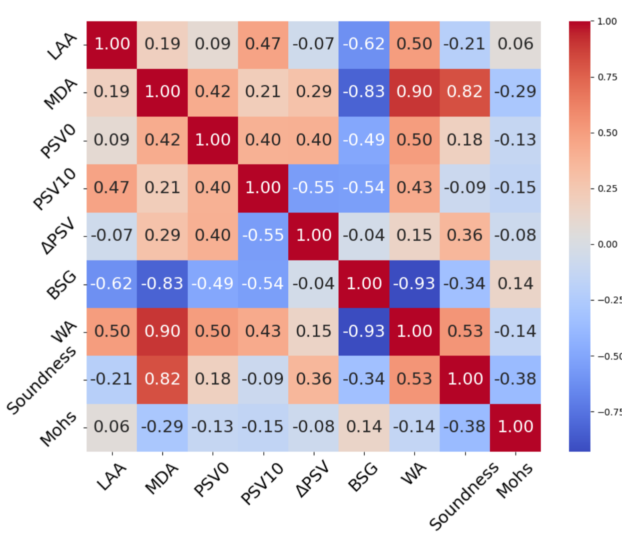


Figure 3.18 Correlation Heatmap (Mechanical vs. Physical Properties).

dolomite is more resistant to abrasion. Conversely, higher WA correlates with increased MDA loss, indicating that more porous dolomite is more vulnerable to abrasion. Increased porosity weakens the aggregate structure, making it more susceptible to mechanical wear and disintegration. Similarly, highly porous dolomites are more prone to weathering, which further affects their abrasion resistance. In addition, LAA exhibits a strong correlation with BSG (-0.62) and a moderate correlation with WA (0.5), reinforcing the relationship between aggregate density, porosity, and wear resistance.

PSV is also linked to both physical and mechanical properties. Initial PSV (PSV0) exhibits a moderate negative correlation with BSG (-0.49) and a moderate positive correlation with WA (0.5), suggesting that denser dolomite tends to have lower initial friction, whereas more porous dolomite exhibits higher initial PSV values. Additionally, PSV0 shows a moderate positive correlation with MDA (0.42), which may be attributed to surface texture characteristics.

Furthermore, PSV10 demonstrates a moderate correlation with LAA (0.47), indicating that aggregates with higher abrasion loss tend to have higher friction after polishing. While this relationship may seem counterintuitive—since aggregates with poor wear resistance are generally expected to exhibit lower friction after polishing—it can be better understood by considering the influence of density and porosity on the polished surface texture.

Table 3.8 presents the correlation coefficients between surface texture sharpness (kurtosis) and various mechanical and physical properties of dolomite at both the initial state (before polishing) and after 10 hr of polishing. The kurtosis parameter quantifies the sharpness and height variations of the aggregate surface, which influences pavement friction.

As shown in Table 3.8, before polishing (Polish Hour = 0), the texture properties of the initial aggregate surface exhibit the following correlations:

- BSG shows a weak negative correlation with peak sharpness (-0.22), suggesting that denser dolomite tends to have a smoother initial surface.

TABLE 3.8
Correlation Coefficient (Texture vs. Mechanical & Physical Properties).

Polish Hour = 0	Kurtosis (Peak Sharpness)
Properties	Total (Macro & Micro)
BSG	-0.22
WA	0.35
Soundness	0.51
LAA	-0.36
MDA	0.55
PSV0	0.28
Polish Hour = 10	Kurtosis (Peak Sharpness)
Properties	Total (Macro & Micro)
BSG	-0.49
WA	0.43
Soundness	-0.07
LAA	0.62
MDA	0.20
PSV10	0.17

Kurtosis (Peak Sharpness) represents the degree of sharpness in the texture profile

- WA exhibits a moderate positive correlation with peak sharpness (0.35), implying that more porous dolomite develops sharper surface features, which may initially enhance friction.
- Soundness demonstrates a moderate to strong positive correlation (0.51), indicating that aggregates with lower weathering resistance tend to have sharper initial surface textures.
- LAA shows a moderate negative correlation (-0.36), suggesting that aggregates with lower impact resistance have higher initial surface roughness.
- MDA exhibits the strongest positive correlation (0.55), implying that dolomites with higher MDA loss (more susceptible to abrasion) tend to have sharper initial surface textures.
- PSV0 correlates positively with peak sharpness (0.28), reinforcing that aggregates with sharper textures before polishing tend to have higher initial friction.

Table 3.8 exhibits that, after 10-hr polishing, the relationships between texture sharpness and aggregate properties shift, reflecting the impact of prolonged polishing:

- BSG shows a stronger negative correlation (-0.49), reinforcing that denser dolomite develops a smoother surface after polishing.
- WA maintains a moderate positive correlation (0.43), suggesting that more porous dolomites retain sharper textures even after extended polishing.
- Soundness displays a weaker correlation (-0.07), indicating that weathering resistance has less influence on polished surface texture than on the initial surface.
- LAA exhibits a strong positive correlation (0.62), highlighting that aggregates with lower impact resistance develop sharper polished textures, possibly maintaining better friction retention.
- MDA correlation weakens (0.20), suggesting that wet abrasion resistance has a reduced effect on final surface sharpness.
- PSV10 maintains a weak correlation (0.17), indicating that sharpness after polishing is not the dominant factor in long-term friction retention.

In summary, the key observations are obtained as follows:

- Denser dolomite (higher BSG) leads to smoother surfaces before and after polishing, reducing friction.
- More porous dolomite (higher WA) retains sharper textures even after extended polishing, which may enhance long-term friction.
- Abrasion resistance (LAA and MDA) significantly influences initial surface sharpness but has a reduced effect on polished textures.
- The correlation between PSV10 and surface sharpness is weaker, suggesting that other factors, such as mineral composition and macrotexture depth, play a role in long-term friction retention.

3.4.2 Correlation Analysis of Chemical Properties

3.4.2.1 Chemical Properties vs. Physical Properties. Magnesium is a key component of dolomite and plays a significant role in influencing its physical properties. As shown in Figure 3.19, magnesium oxide exhibits a moderate positive correlation with both BSG and Mohs hardness, while showing a strong negative correlation with WA and soundness. This suggests that dolomite with higher magnesium content tends to be denser and less porous, leading to lower water absorption and improved freeze-thaw resistance. Additionally, higher magnesium content enhances dolomite's hardness, contributing to greater mechanical strength and durability.

Similarly, calcium oxide demonstrates a moderate positive correlation with hardness, reinforcing its role in strengthening the aggregate structure. In contrast, aluminum oxide, silicon dioxide, and titanium dioxide exhibit negative correlations with BSG and Mohs hardness while showing positive correlations with WA and soundness. This indicates that dolomite with higher aluminum, silicon, and titanium content tends to be less dense, softer, more porous, and more susceptible to weathering and degradation. Additionally, iron oxide exhibits a moderate negative correlation with hardness and a strong positive correlation with soundness, further suggesting its association with reduced durability.

While these findings align with some established trends, they also highlight notable exceptions. Typically, aggregates

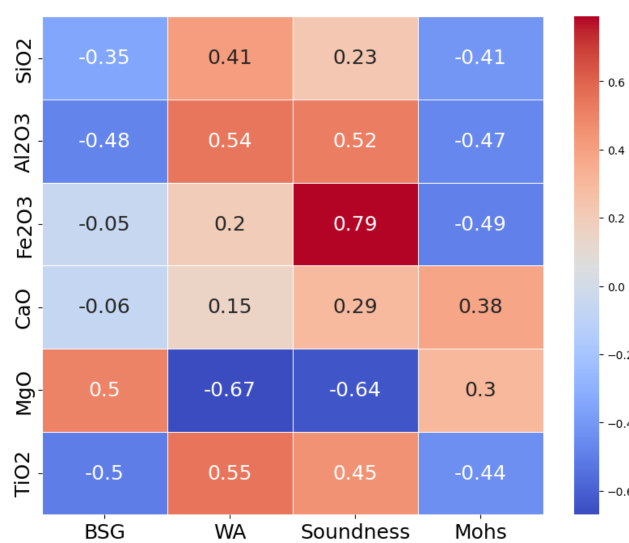


Figure 3.19 Correlation Heatmap (Physical vs. Chemical Properties).

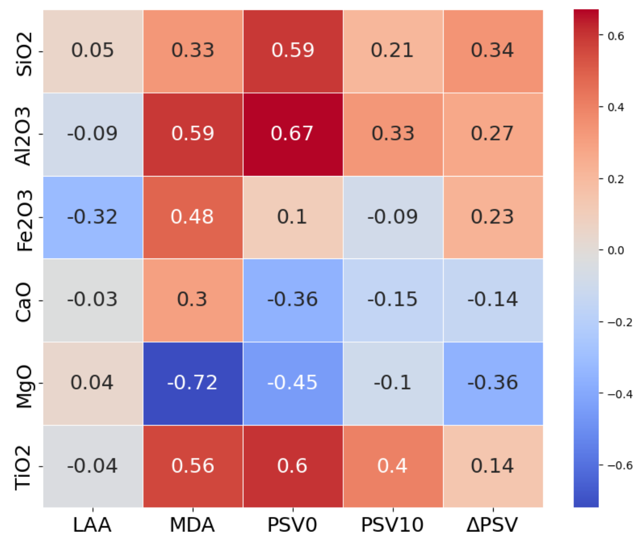


Figure 3.20 Correlation Heatmap (Mechanical vs. Chemical Properties).

with higher aluminum and titanium content are associated with increased hardness, whereas calcium and magnesium are thought to reduce hardness (Bao et al., 2024; Li et al., 2017; Li et al., 2021). Additionally, higher aluminum content is generally correlated with an increase in BSG (Li et al., 2017). These deviations arise due to the complex roles of chemical components in different aggregate types. Since aggregates contain distinct minor and trace elements, their influence on mechanical performance varies. Thus, while correlation analysis provides a broad overview of interactions between physical, mechanical, and chemical properties, the specific impact of individual chemical components depends on the aggregate type.

3.4.2.2 Chemical Properties vs. Mechanical Properties. Figure 3.20 illustrates the correlations between mechanical and chemical properties. Although magnesium oxide does not significantly affect dry wear resistance, it exhibits strong abrasion resistance in wet conditions (correlation coefficient = -0.72). Additionally, magnesium oxide shows a moderate negative correlation with PSV0 and ΔPSV, indicating that while higher magnesium content initially reduces friction performance, it enhances long-term friction retention by slowing the rate of polishing-induced friction loss. Similarly, calcium oxide exhibits a moderate negative correlation with PSV0, reinforcing its influence on initial friction.

In contrast, silicon, aluminum, and titanium demonstrate greater susceptibility to wear under wet conditions. However, their concentrations show moderate to strong positive correlations with PSV0 and weaker correlations with PSV10 and ΔPSV. This suggests that while these elements contribute to higher initial friction performance, their role in long-term friction retention is less pronounced. Meanwhile, iron oxide shows a moderate negative correlation with LAA loss and a moderate positive correlation with MDA loss, likely due to the oxidation and deterioration of iron-based compounds in humid environments.

TABLE 3.9
Correlation Coefficients (Texture vs. Chemical Properties).

Before Polishing	
Polish Hour = 0	Kurtosis (Peak Sharpness)
Properties	Total (Macro & Micro)
SiO_2	0.18
Al_2O_3	0.38
Fe_2O_3	0.32
CaO	0.25
MgO	-0.53
TiO_2	0.37
After Polishing	
Polish Hour = 10	Kurtosis (Peak Sharpness)
Properties	Total (Macro & Micro)
SiO_2	0.17
Al_2O_3	0.10
Fe_2O_3	-0.13
CaO	-0.05
MgO	-0.16
TiO_2	0.11

Kurtosis (Peak Sharpness) represents the degree of surface texture sharpness.

3.4.2.3 Chemical Properties vs. Surface Texture. Table 3.9 presents the correlation coefficients between surface texture and chemical composition before and after polishing.

Before Polishing (Polish Hour = 0): Before undergoing polishing, the chemical properties of dolomite exhibit notable correlations with surface texture roughness, as indicated by kurtosis values.

1. Magnesium Oxide and Surface Texture:
   - Magnesium oxide shows a moderate negative correlation (-0.53) with overall texture roughness.
   - This aligns with its strong relationship with BSG and WA, where higher magnesium content leads to increased density and reduced porosity.
   - Since calcium magnesium carbonate ($CaMg(CO_3)_2$) is the primary component of dolomite, its higher concentration results in a more compact structure and a smoother surface texture.
2. Aluminum Oxide, Iron Oxide, and Titanium Dioxide:
   - Positive correlations with overall texture roughness (aluminum oxide: 0.38, iron oxide: 0.32, titanium dioxide: 0.37) suggest that these elements contribute to a rougher surface before polishing.
   - As minor components (<1%), they likely disrupt the compact crystalline structure of $CaMg(CO_3)_2$, leading to increased porosity and a rougher initial texture.
   - This increased roughness enhances PSV0, explaining why dolomite with higher aluminum, iron, and titanium contents often exhibits better friction performance before polishing.
3. Silicon Dioxide and Calcium Oxide:
   - Silicon dioxide (0.18) and calcium oxide (0.25) show weaker positive correlations with initial surface roughness.
   - While silicon dioxide is known for improving wear resistance in other aggregates (e.g., quartzite), its effect on dolomite's surface texture appears less pronounced.
   - Calcium oxide's influence is moderate, as it is part of the dolomite matrix but does not significantly disrupt its crystalline structure.

After Polishing (Polish Hour = 10): Following polishing, the correlations between chemical composition and surface texture undergo significant changes.

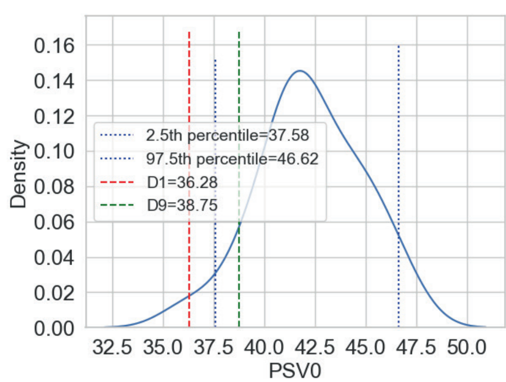
1. Magnesium Oxide and Calcium Oxide Show Weakened Negative Correlations:
   – Magnesium oxide (-0.16) and calcium oxide (-0.05) retain their negative correlations but at much lower magnitudes.
   – This suggests that polishing diminishes the influence of density and porosity on texture roughness.
   – The initial smoothing effect of higher magnesium and calcium content is less relevant after prolonged wear, indicating that long-term friction retention depends on other factors.
2. Reduction in Influence of Aluminum Oxide, Iron Oxide, and Titanium Dioxide:
   – Aluminum oxide's correlation drops from 0.38 to 0.10, iron oxide shifts from 0.32 to -0.13, and titanium dioxide from 0.37 to 0.11.
   – This suggests that the initial roughness created by these trace elements is significantly reduced during the polishing process.
   – The surface irregularities caused by these minor oxides are smoothed out, leading to a more uniform texture and decreased friction performance over time.
3. Silicon Dioxide Remains Relatively Stable:
   – The correlation for silicon dioxide (0.18 → 0.17) remains nearly unchanged.
   – This suggests that silicon dioxide-rich aggregates retain their texture features better during wear, possibly contributing to long-term friction performance.

The main findings of effects of chemical components on surface textures are:

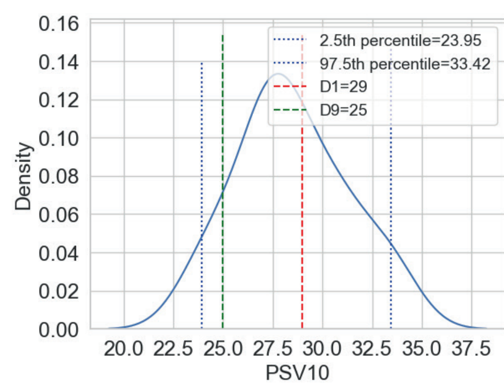
1. Before Polishing: Chemical components such as magnesium oxide and calcium oxide contribute to smoother, denser surfaces, while aluminum oxide, iron oxide, and titanium dioxide create rougher textures with higher porosity.
2. After Polishing: The influence of magnesium oxide and calcium oxide weakens, and aluminum oxide, iron oxide, and titanium dioxide no longer contribute to roughness, as polishing erodes their initial texture effects.
3. Long-Term Friction Performance: Silicon dioxide shows consistent texture retention, indicating that it may play a role in maintaining frictionover time.

3.5 Properties of Investigated Dolomite Samples

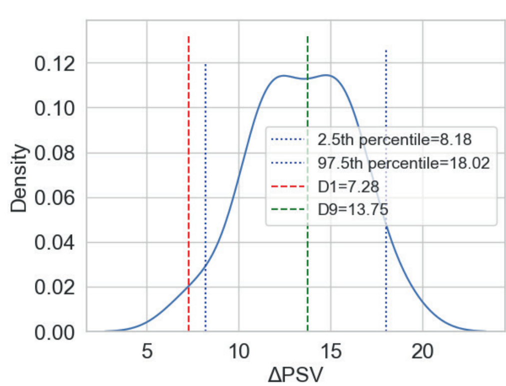
Previous studies have primarily focused on the impact of PSV10 and ΔPSV, but insufficient PSV0 can lead to a rapid decline in friction performance soon after roads are opened to traffic. Figure 3.21 presents the distributions of PSV0, PSV10,



(a) Distribution of PSV0



(b) Distribution of PSV10



(c) Distribution of ΔPSV

Figure 3.21 Distributions of PSV0, PSV10, and ΔPSV.

and ΔPSV, with key dolomite sources D1 and D9 highlighted for comparison:

- The red dashed line represents source D1, while the green dashed line represents source D9.
- The blue dashed lines indicate the 2.5th and 97.5th percentiles, providing an overall reference for the distribution range.

The following key observations from Figure 3.21 are as follows:

- PSV0: D1 exhibits one of the lowest initial PSV values, falling below the 2.5th percentile, indicating particularly weak initial friction. Although D9's PSV0 falls within the 95% confidence interval, it is still on the lower end.
- PSV10: Despite their low initial friction, both D1 and D9 remain within the marginal performance category after 10 hours of polishing.
- ΔPSV: D1 exhibits the smallest ΔPSV, indicating minimal friction loss over time, whereas D9 has a ΔPSV near the median (13.72), suggesting moderate friction retention.

These findings suggest that the poor friction performance observed in road sections containing D1 and D9 is primarily due to their initially low PSV0, rather than excessive friction loss (ΔPSV) over time. This observation aligns with the statistical outcomes presented in Table 3.6.

3.5.1 Mechanical Properties: LAA and MDA

Figure 3.22 illustrates the distributions of LAA and MDA losses, key indicators of wear resistance. The figure shows the following distributions:

- LAA Loss: Some dolomite sources exceed 30% LAA loss, but all remain below the upper 50% limit (Figure 3.22a). D1 and D9 both exhibit below-median LAA loss (median = 27.63%), indicating better impact resistance.
- MDA Loss: Most dolomite sources fall below 18% MDA loss, except for D16 (Figure 3.22b).
  - D1 has a particularly low MDA loss, approaching the 2.5th percentile, suggesting excellent resistance to wet abrasion.
  - D9 has a moderate MDA loss, close to the median (11.4%).

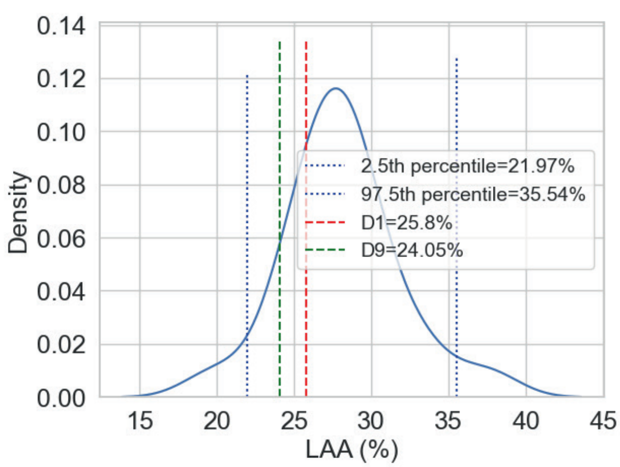
These trends align with the ΔPSV distribution (Figure 3.21c), where:

- D1 exhibits minimal friction loss (low ΔPSV), correlating with its low MDA loss.
- D9, with a mid-range MDA loss, also falls within the median ΔPSV range.

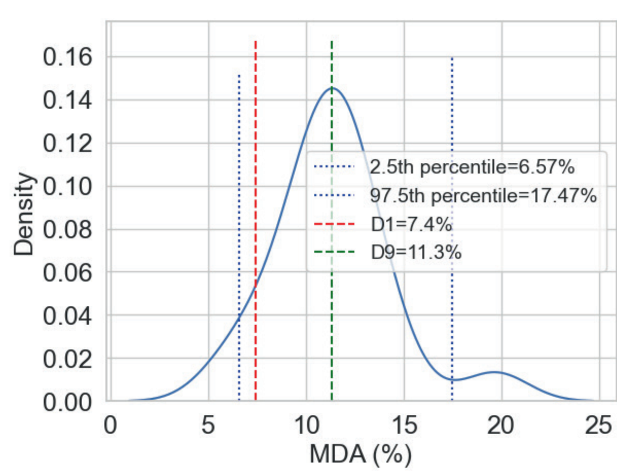
3.5.2 Physical Properties

Figure 3.23 presents the distribution of key physical properties, including BSG, WA, soundness, and hardness. The following key observations are obtained from the figure:

- BSG and WA:
  - D1 has the highest BSG (2.75), and D9 also has an above-median BSG (median = 2.64).
  - Both D1 and D9 exhibit exceptionally low WA, near the 2.5th percentile, indicating a dense structure with minimal voids.
  - Higher BSG and lower WA indicate reduced porosity, which is linked to lower PSV0.
- Soundness:
  - Soundness loss ranges from 0.38% to 7.00%, with most sources below 3%.
  - D1 exhibits a low soundness value, indicating high resistance to freeze-thaw cycles.
  - D9 has a soundness value above the median (1.18%), suggesting slightly lower durability.
  - This aligns with the ΔPSV results, where D1 had minimal friction loss, while D9 exhibited moderate PSV reduction.
- Hardness (Mohs Scale):
  - D1 has the highest hardness value (3.7), whereas D9 has a relatively low hardness, near the 2.5th percentile.
  - Higher hardness (D1) generally correlates with better long-term wear resistance but may contribute to lower initial friction (PSV0).

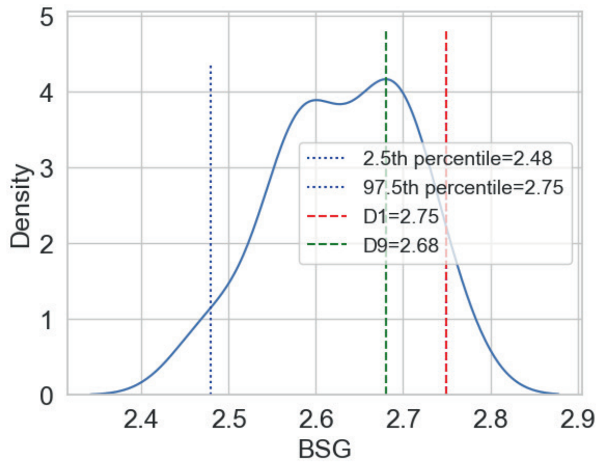


(a) Distribution of LAA (%)

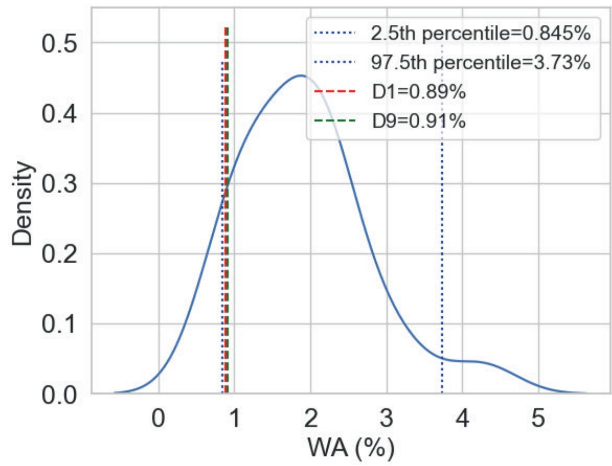


(b) Distribution of MDA (%)

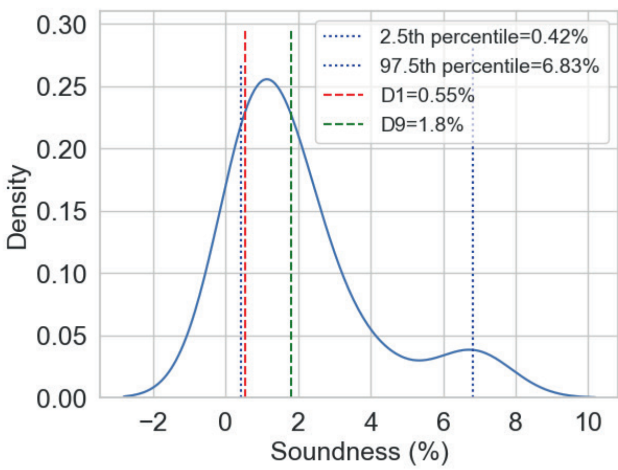
Figure 3.22 Distributions of LAA and MDA.



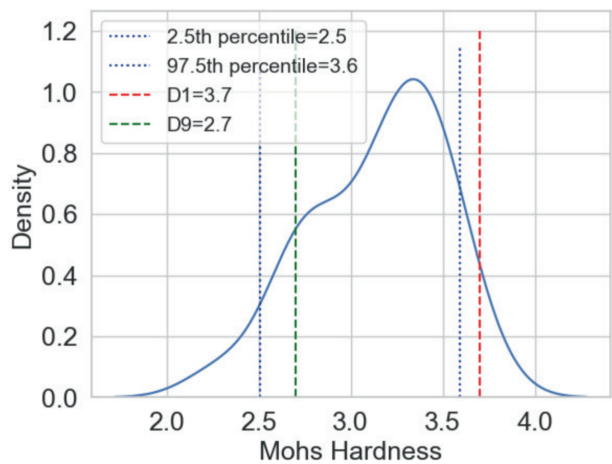
(a) Distribution of BSG



(b) Distribution of WA (%)



(c) Distribution of Soundness



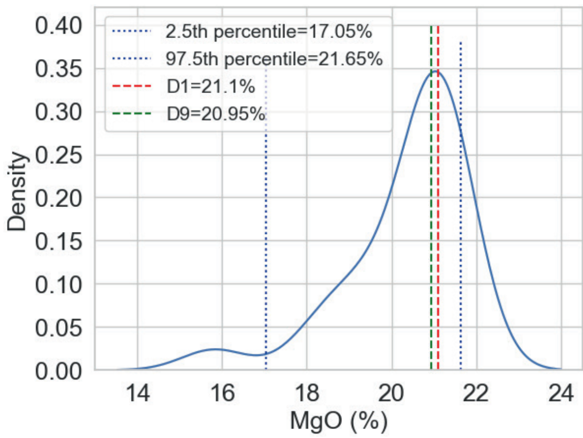
(d) Distribution of Hardness

Figure 3.23 Distributions of Physical Properties.

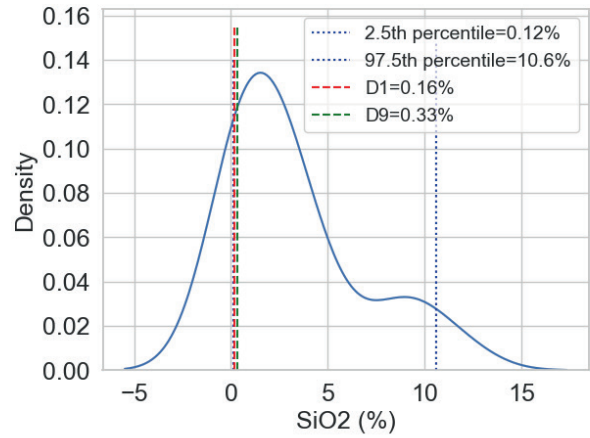
3.5.3 Chemical Properties

The chemical composition of dolomite plays a crucial role in determining its mechanical, physical, and frictional properties. Figure 3.24 illustrates the distributions of key chemical components, including magnesium oxide, silicon dioxide, aluminum oxide, iron oxide, calcium oxide, and titanium dioxide. The following key observations are obtained from the figure:

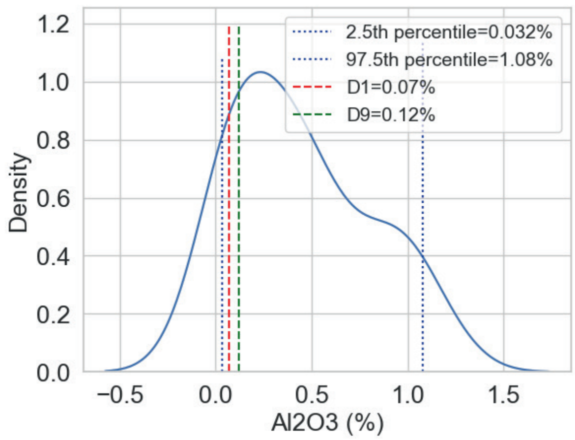
- Magnesium Oxide:
  - Both D1 and D9 have above-median magnesium oxide content, at 21.10% and 20.95%, respectively (Figure 3.24a).
  - Magnesium contributes to increased density and reduced porosity, lowering PSV0.
  - Higher magnesium content is associated with stronger wear resistance but may lead to smoother surfaces, reducing initial friction.
- Silicon Dioxide:
  - D1 and D9 exhibit relatively low silicon content (Figure 3.24b).
  - Silicon is positively correlated with PSV0, meaning lower silicon content may contribute to their weak initial friction performance.
- Aluminum Oxide and Titanium Dioxide:
  - Both D1 and D9 have relatively low aluminum and titanium contents (Figure 3.24c & Figure 3.24f).
  - Higher aluminum and titanium contents correlate with rougher surface textures and better initial friction.
  - The lack of these elements in D1 and D9 may contribute to their low PSV0.
- Calcium Oxide:
  - D1 and D9 exhibit relatively high calcium oxide concentrations (Figure 3.24e).
  - Calcium is positively correlated with PSV0, but its effect is weaker than silicon.



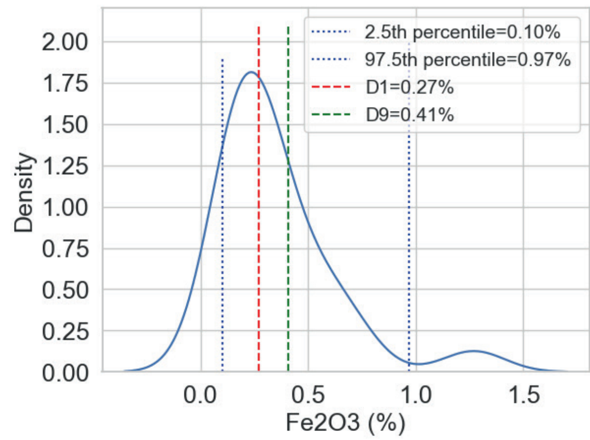
(a) Distribution of Magnesium Oxide (%)



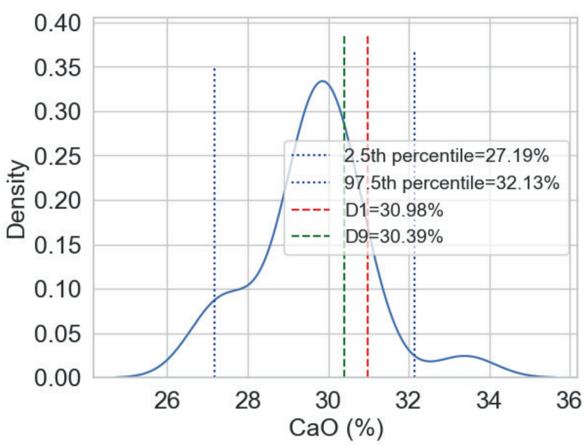
(b) Distribution of Silicon Dioxide (%)



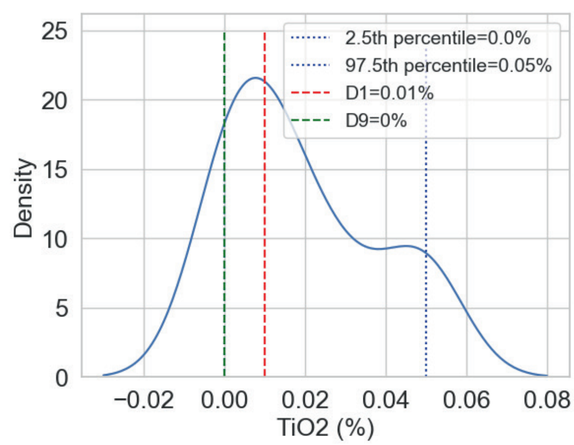
(c) Distribution of Aluminum Oxide (%)



(d) Distribution of Iron Oxide (%)



(e) Distribution of Calcium Oxide (%)



(f) Distribution of Titanium Dioxide (%)

Figure 3.24 Distributions of Chemical Properties.

TABLE 3.10
T-Test Results for Chemical Components of D1 and D9 Compared to Other Aggregates.

	D1			D9		
Chemical Components	**T-Statistic**	**P-Value**	**Significant ($p < 0.05$)**	**T-Statistic**	**P-Value**	**Significant ($p < 0.05$)**
MgO	-2.441	0.0246	Yes	-1.985	0.0617	No
SiO_2	4.347	0.0003	Yes	4.127	0.0006	Yes
Al_2O_3	5.19	0.0001	Yes	4.559	0.0002	Yes
Fe_2O_3	1.306	0.2072	No	-0.924	0.3672	No
CaO	-4.643	0.0002	Yes	-2.772	0.0121	Yes
TiO_2	2.502	0.0217	Yes	4.884	0.0001	Yes

  – While calcium content in D1 and D9 is high, their lower silicon, aluminum, and titanium levels may have a stronger influence on reducing their PSV0 values.
- Iron Oxide:
  – Both D1 and D9 have above-median iron oxide content but remain within a low to moderate range (Figure 3.24d).
  – Iron is not significantly correlated with friction performance but affects abrasion resistance.
  – Higher iron content can indicate greater susceptibility to oxidation and weathering.

Table 3.10 presents the results of one-sample t-tests comparing the chemical compositions of D1 and D9 with those of other dolomites. For D1, magnesium oxide, calcium oxide, silicon dioxide, aluminum oxide, and titanium dioxide contents differed significantly, indicating distinct compositional characteristics. D9 also showed significant differences in calcium oxide, silicon dioxide, aluminum oxide, and titanium dioxide. Although the p-value for magnesium oxide in D9 was slightly above the conventional threshold ($p = 0.0617$), the consistent direction and magnitude of the difference, together with the significant result observed for D1 reinforce the interpretation the magnesium plays a meaningful role in differentiating aggregate properties. The lack of significance for iron oxide in both cases suggests it may have limited influence on the observed variations.

By analyzing the mechanical, physical, and chemical properties of the dolomite samples, the following findings are obtained:

- D1 and D9 exhibit some of the lowest PSV0 values, suggesting weak initial friction performance.
- Despite this, their PSV10 values remain in the marginal category, indicating that their friction retention is moderate.
- Both D1 and D9 exhibit high BSG, low WA, and dense structures, contributing to their reduced initial friction.
- Their low silicon dioxide, aluminum oxide, and titanium dioxide levels further contribute to their weak PSV0.
- D1, with its high hardness and low ΔPSV, experiences minimal friction loss over time, while D9 shows moderate PSV reduction.
- Although chemical properties play a critical role, the initial texture of these aggregates is a key factor in their friction performance.

These findings suggest that while D1 and D9 may not experience excessive friction loss over time (low ΔPSV), their low initial PSV0 values make them less suitable for applications requiring high initial friction.

3.6 Clustering Analysis of Dolomite Properties

The properties of dolomite can be broadly classified into two key aspects: abrasion resistance and initial friction. High initial friction ensures optimal friction at the beginning of a road's service life, whereas strong abrasion resistance helps maintain friction over time by minimizing excessive wear and polishing effects.

As a critical component of dolomite, magnesium significantly influences both properties. Previous analyses indicate that higher magnesium content enhances abrasion resistance but reduces initial friction, while lower magnesium content improves initial friction at the cost of reduced abrasion resistance. To optimize dolomite performance, a hierarchical clustering algorithm was employed to classify friction performance, with a primary emphasis on magnesium oxide as the key determinant. Based on the clustering results, a decision tree model was constructed to determine the optimal segmentation of magnesium oxide content for dolomite classification.

3.6.1 Clustering Analysis for PSV0 Retention

In addition to $CaMg(CO_3)_2$, dolomite also contains calcium carbonate ($CaCO_3$). Calcium and magnesium are the predominant chemical components in dolomite. Correlation analysis revealed that calcium oxide exhibited a weaker correlation with PSV0 than magnesium oxide, yet still fell within the moderate correlation range. This suggests that calcite mitigates the negative effect of $CaMg(CO_3)_2$ on initial friction (PSV0).

Given these findings, magnesium oxide, calcium oxide, and PSV0 were used as input variables for hierarchical clustering to classify the 22 dolomite sources based on their chemical composition and initial friction performance. Figure 3.25 presents the dendrogram derived from hierarchical clustering, illustrating the grouping of dolomite sources into distinct clusters.

- Cluster 1: Characterized by a high magnesium oxide content and relatively low PSV0, indicating strong abrasion resistance but weaker initial friction.
- Cluster 2: Exhibits a lower magnesium oxide content and relatively high PSV0, suggesting improved initial friction performance.
- Cluster 3: Contains only a single dolomite source (D16) with an abnormally low magnesium oxide content (15.82%), which falls well below INDOT's minimum defined boundary of 17.08%.

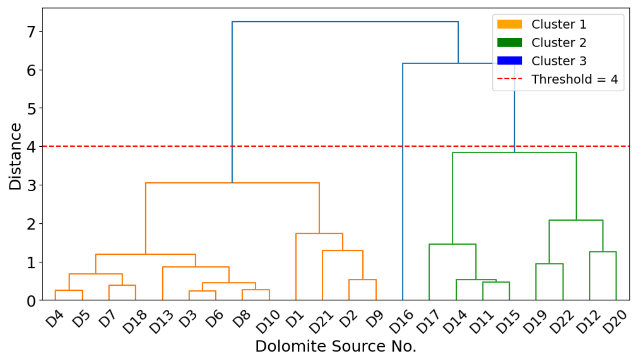


Figure 3.25 Hierarchical Clustering Dendrogram (Magnesium Oxide, Calcium Oxide, and PSV0). The Clustering Results Divided the 22 Dolomite Sources Into Three Groups, as Shown in Table 3.11.

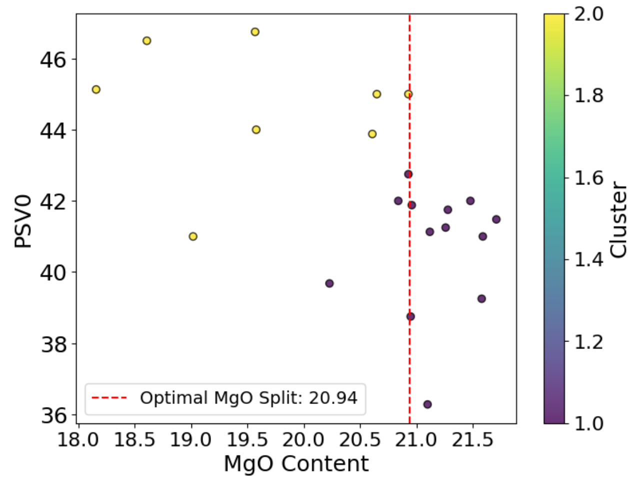


Figure 3.26 Decision Tree-Based Segmentation of Magnesium Oxide vs. PSV0.

The high calcium oxide content (33.41%) suggests a greater proportion of calcite, contributing to its relatively high PSV0.

Since Cluster 3 represents an outlier due to its unusually low magnesium oxide content, it was excluded from further analysis in determining the optimal magnesium oxide threshold.

3.6.2 Decision Tree-Based Segmentation of Magnesium oxide Content

To determine the optimal magnesium oxide threshold for initial friction performance (PSV0), a decision tree classifier was implemented. This model was trained using magnesium oxide content as the independent variable, identifying an optimal threshold for classifying dolomite samples based on their PSV0 performance.

Using the entropy criterion, the decision tree model maximized information gain to establish the best classification boundary. The results, presented in Figure 3.26, indicate that:

- Dolomite samples with magnesium oxide content exceeding 20.94% generally exhibit lower PSV0 values, confirming the negative impact of high magnesium content on initial friction.
- Therefore, an magnesium oxide content of 20.94% (equivalent to magnesium = 12.63%) is established as the threshold for distinguishing dolomite performance.

This segmentation offers valuable insights into material selection, as it enables the identification of dolomite sources with an optimal balance between initial friction and long-term wear resistance.

The key findings from clustering analysis are listed below:

- Dolomite sources with higher magnesium oxide content (>20.94%) tend to exhibit lower PSV0 but better abrasion resistance.
- Dolomite sources with lower magnesium oxide content (<20.94%) generally have higher PSV0, making them more suitable for applications requiring strong initial friction.
- Calcite content influences PSV0 positively, partially offsetting the friction-reducing effects of high magnesium oxide concentrations.
- A decision tree-based segmentation confirms 20.94% magnesium oxide as the critical threshold separating high- and low-PSV0 dolomites.

These findings provide a scientific basis for selecting and optimizing dolomite aggregates in pavement applications, ensuring a balance between initial friction performance and long-term durability.

3.6.3 Clustering Analysis for ΔPSV Stability

To further assess the impact of magnesium oxide on friction retention, hierarchical clustering was performed using magnesium oxide and ΔPSV as input variables. Since calcium oxide exhibits only a weak correlation with ΔPSV, it was excluded from the clustering process. The objective was to determine an optimal magnesium oxide threshold that minimizes ΔPSV, thereby identifying dolomite sources with superior friction retention over time. The resulting dendrogram, presented in

TABLE 3.11
Cluster Characteristics (Magnesium Oxide, Calcium Oxide, and PSV0).

No.	MgO				CaO				PSV0			
	Mean	STD	Min	Max	Mean	STD	Min	Max	Mean	STD	Min	Max
1	21.16	0.40	20.23	21.71	30.07	0.52	29.19	30.98	40.71	1.77	36.28	42.75
2	19.64	1.02	18.16	20.93	28.42	1.11	26.97	29.73	44.66	1.80	41.00	46.75
3	15.82	-	15.82	15.82	33.41	-	33.41	33.41	43.50	-	43.50	43.50

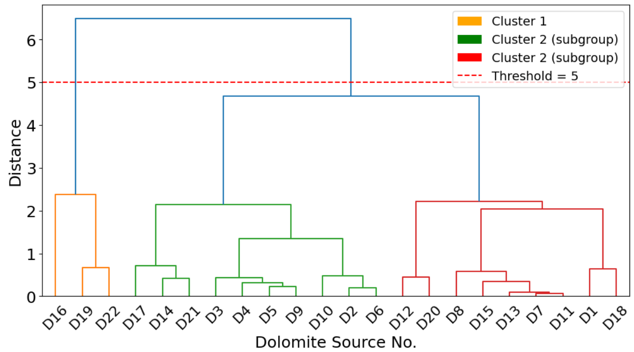


Figure 3.27 Hierarchical Clustering Dendrogram (Magnesium Oxide and ΔPSV).

TABLE 3.12
Cluster Characteristics (Magnesium oxide [MgO] and ΔPSV).

	MgO				ΔPSV			
No.	**Mean**	**STD**	**Min**	**Max**	**Mean**	**STD**	**Min**	**Max**
1	17.53	1.50	15.82	18.61	17.23	1.67	15.55	18.88
2	20.81	0.74	19.02	21.71	12.87	2.49	7.28	16.40

Figure 3.27, classifies the 22 dolomite sources into two distinct clusters, reflecting different levels of friction retention after polishing.

The statistical characteristics of the two clusters are summarized in Table 3.12:

- Cluster 1: Characterized by a lower magnesium oxide content and a higher ΔPSV, indicating that these dolomites experience significant friction loss after 10 hours of polishing.
- Cluster 2: Exhibits a higher magnesium oxide content and a lower ΔPSV, suggesting greater resistance to polishing and more stable friction performance over time.

These results indicate that dolomites with magnesium oxide content above 18.82% generally exhibit lower ΔPSV values, meaning they are more resistant to friction loss after polishing.

To further validate this threshold, a decision tree classifier was applied to determine the optimal magnesium oxide boundary for minimizing ΔPSV. As shown in Figure 3.28, the decision tree model identifies 18.82% as the critical magnesium oxide threshold, beyond which dolomite samples generally retain friction more effectively. It should be noted that 18.82% of magnesium oxide content is equivalent to 11.35% of magnesium content.

3.7 Exploration of Magnesium Oxide Range and Source Characteristics

Based on the clustering analysis, two critical magnesium oxide thresholds (18.82% and 20.94%) were identified, dividing dolomite samples into three performance groups:

1. Low Magnesium Oxide Content (< 18.82%)
   – Highest initial friction (PSV0)
   – Greatest friction loss (high ΔPSV)
   – Potential risk of lower long-term friction retention
2. Moderate Magnesium oxide Content (18.82–20.94%)
   – Balanced performance in both PSV0 and PSV10
   – Moderate ΔPSV
   – Most sustainable option for long-term pavement friction
3. High Magnesium Oxide Content (>20.94%)
   – Lower PSV0
   – Reduced friction loss (lower ΔPSV)
   – Potential concern for inadequate friction at early pavement life

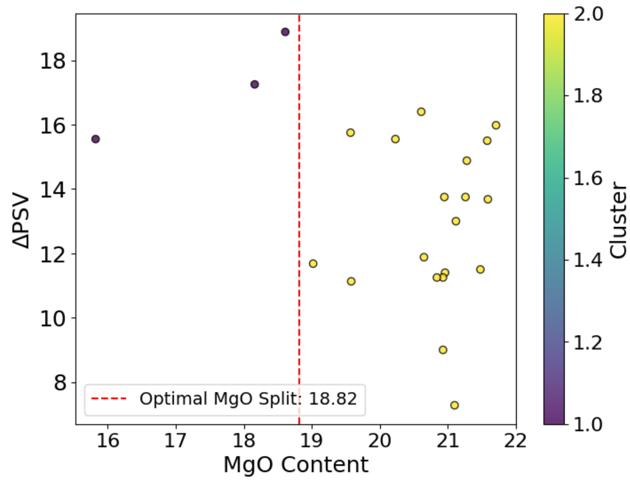


Figure 3.28 Decision Tree-Based Segmentation of Magnesium Oxide vs. ΔPSV.

Figure 3.29 presents the boxplots of PSV0, PSV10, and ΔPSV across the three magnesium oxide content ranges, highlighting the following trends:

- Dolomite samples with magnesium oxide content below 18.82% (magnesium < 11.35%) show the highest PSV0, but they also exhibit the highest ΔPSV, indicating greater friction loss over time.
- Dolomite samples with magnesium oxide content between 18.82% and 20.94% (11.35% ≤ magnesium ≤ 12.63%) strike a balance between initial friction and long-term durability, making them an optimal choice for sustained pavement performance.
- Dolomite samples with magnesium oxide content above 20.94% (magnesium > 12.63%) generally exhibit lower PSV0, potentially affecting the initial friction performance of roadways. Additionally, PSV10 values for this group are lower than those in the moderate magnesium oxide range (18.82–20.94%), indicating that these dolomites may experience greater friction loss after polishing.

3.7.1 Magnesium Oxide Content Distribution by Producer

To examine variations in magnesium oxide content across different producers, Figure 3.30 presents the magnesium oxide content distribution for each dolomite supplier. The dolomite sources associated with each producer are listed as follows:

- P1: D1 to D8
- P2: D9 to D11
- P3: D12 to D15

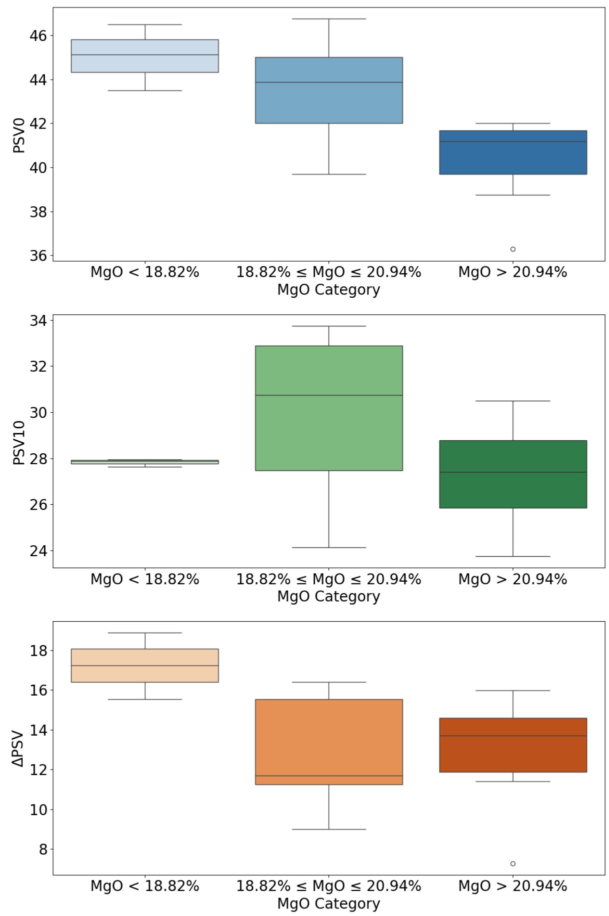


Figure 3.29 Boxplot for Different Magnesium Oxide Ranges.

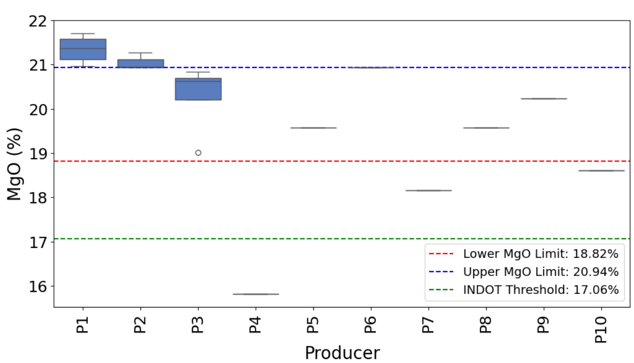
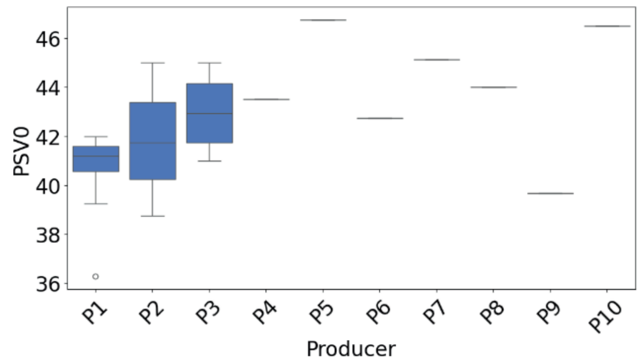


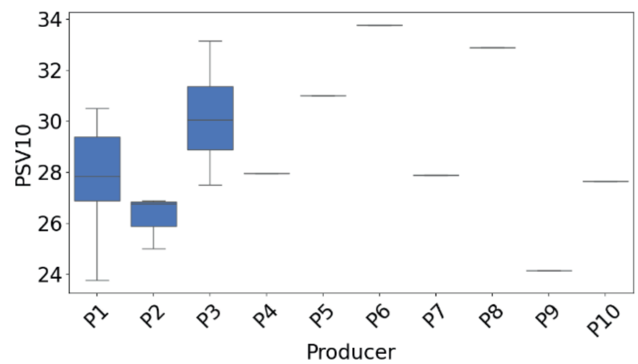
Figure 3.30 Magnesium oxide Content Distribution by Producer.

- P4: D16
- P5: D17
- P6: D18
- P7: D19
- P8: D20
- P9: D21
- P10: D22

The key thresholds (18.82% and 20.94%) are marked with blue and red dashed lines, while the INDOT-defined minimum



(a) PSV0



(b) PSV10

Figure 3.31 PSV0 and PSV10 Distribution by Producer.

magnesium oxide threshold (17.06%) is shown with a green dashed line. The key observations are as follows:

- Dolomite sources from P1 and two sources from P2 exceed 20.94% magnesium oxide, meaning they are more resistant to friction loss but have lower initial friction.
- Dolomite sources from P4, P7, and P10 contain less than 18.82% magnesium oxide, meaning they have higher initial friction but may experience greater friction loss over time.
- Nine dolomite sources from six producers (P2, P3, P5, P6, P8, and P9) fall within the 18.82–20.94% magnesium oxide range, meaning they offer the best balance between initial friction and long-term durability.

3.7.2 PSV0 and PSV10 Distribution by Producer

Figure 3.31 presents the PSV0 and PSV10 distributions for each producer, revealing the following trends:

- Dolomites from P1 and P2 generally fall within the acceptable PSV0 range, but they remain lower than those within the 18.82–20.94% magnesium oxide range, confirming their lower initial friction performance.
- Dolomites from P4, P7, and P10 exhibit higher PSV0 values, primarily due to their lower magnesium oxide content (< 18.82%). However, P4's magnesium oxide content is significantly below 17.06%, meaning that D16 from P4 would not qualify as dolomite under INDOT standards.
- Dolomites from P3, P5, P6, and P8 provide both acceptable PSV0 and PSV10 values, indicating that these sources not only provide

sufficient initial friction but also maintain adequate long-term friction.

3.7.3 *Influence of Other Chemical Components on Friction Performance*

While magnesium oxide plays a dominant role in dolomite friction performance, other chemical components may also contribute to friction loss over time. Figure 3.32 presents scatter plots of key chemical components, identifying potential outliers that may influence dolomite performance.

- D21 from P9 exhibits unusually high iron oxide content, exceeding the 2-standard deviation (2-SD) threshold. Since iron oxide positively correlates with MDA (0.48) and Soundness (0.79), its excessive concentration may contribute to greater friction loss (higher ΔPSV).
- D19 from P7 shows silicon dioxide content above the 2-SD threshold, which correlates positively with PSV0 (0.59) but weakly with ΔPSV (0.34). This suggests that silicon dioxide enhances initial friction but has a limited effect on long-term friction retention.
- D16 from P4 exhibits exceptionally high calcium oxide content (33.41%) and abnormally low magnesium oxide content (15.82%), making it ineligible under INDOT dolomite classification standards. The high calcite concentration results in high initial friction but also greater friction loss (ΔPSV = 15.55) after polishing.

3.8 Field-Collected Aggregate Friction Property Analysis

To further investigate the factors contributing to low friction performance observed in newly paved road segments, aggregates were extracted from field-collected cores. These segments primarily incorporated D1 and D9 dolomites, both of which were identified as having low and unstable PSV0 in laboratory testing.

The extracted aggregates, ranging in size from 6.3–9.5 mm, were used to create test coupons for PSV testing. In each of the 14 road segments, aggregates were obtained from one of three designated zones, with three coupons prepared per segment. The PSV0 and PSV10 values were determined by selecting the lowest PSV from each coupon and averaging the results within each group.

3.8.1 *Comparison of Field-Collected vs. Laboratory-Tested PSV Values*

Figure 3.33 presents scatter plots of PSV0 and PSV10 for aggregates extracted from field-collected cores. The horizontal axis represents road segments, where "Z1" and "Z2" denote Zone 1 and Zone 2 within each segment. The vertical axis displays PSV values before and after 10 hr of polishing, offering insights into the friction performance of in-field aggregates. In the figure, blue points indicate road segments using D1 dolomite, while orange points indicate segments containing D9 dolomite.

The following findings can be observed in Figure 3.33:

- For D1 aggregates:
  - Except for the sample from SR 26 Z1 (*PSV0 = 35.17*), all other field-collected aggregates exhibited higher PSV0 values than the average PSV0 recorded in the laboratory (*ranging from 36.67 to 41.17*), though still within or approaching the overall laboratory range of 34 to 41.
  - After 10 hr of polishing, the PSV10 values ranged from 26.33 to 34.67, which aligns with or exceeds the PSV10 values observed in laboratory tests.
  - An exception is noted in US 36 EH, where the field-collected aggregates exhibited slightly lower PSV10 values than the laboratory samples.
- For D9 aggregates:
  - Three road segments exhibited low friction performance when using D9 aggregates.
  - Except for the sample extracted from US 421 Z2, the PSV0 values of other in-field D9 aggregates were lower than the average PSV0 of D9 tested in the laboratory.
  - However, even after 10 hr of polishing, the PSV10 values of all three road segments remained higher than those of the laboratory-tested D9.

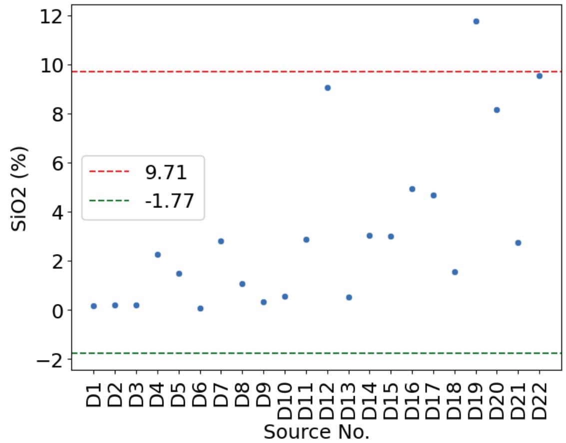
3.8.2 *Influence of Traffic Wear and Aggregate Composition*

Figure 3.34 provides boxplots comparing PSV0 and PSV10 distributions for in-field aggregates and laboratory-tested dolomites categorized by magnesium oxide content. The key findings from this figure include:

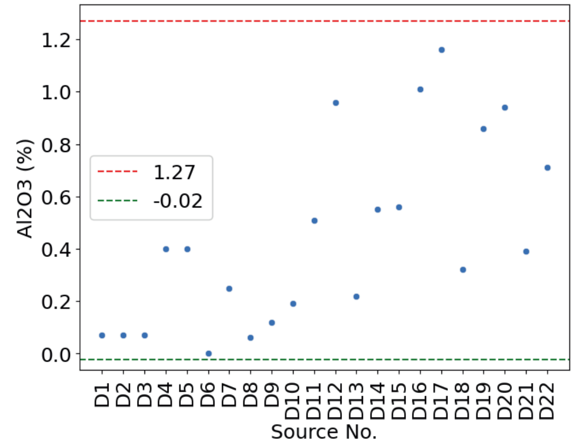
1. Impact of Traffic Load on PSV0:
   - Aggregates from field-collected cores containing D1 exhibited higher PSV0 values than laboratory samples but remained lower than the minimum PSV0 observed in the magnesium oxide > 20.94% category.
   - This discrepancy may be attributed to wear induced by traffic loads.
   - The correlation coefficient between ΔPSV and AADT (Average Annual Daily Traffic) is 0.51, indicating a moderate positive correlation. This suggests that high traffic volumes contribute to increased wear and friction loss over time.
2. Influence of Other Aggregate Types on PSV10:
   - PSV10 values from in-field aggregates were generally higher than any group measured in the laboratory.
   - This suggests that other aggregate types (e.g., steel slag) present in the mixture may have influenced friction retention.
   - During extraction, it was challenging to differentiate dolomite from other aggregates within field-collected cores.
   - The presence of additional aggregates may have helped reduce wear during polishing but did not improve the intrinsic friction properties of dolomite itself.
3. Friction Loss Due to Insufficient Initial PSV0:
   - Lower PSV0 values observed in field-collected aggregates suggest that the low friction in these road segments is primarily due to the inherently poor initial friction of the dolomite itself, rather than excessive polishing.
   - This reinforces the importance of ensuring adequate PSV0 values for aggregates before pavement placement to mitigate early-stage friction deficiencies.

3.9 Recommended Magnesium oxide Threshold and Implications for Pavement Friction Performance

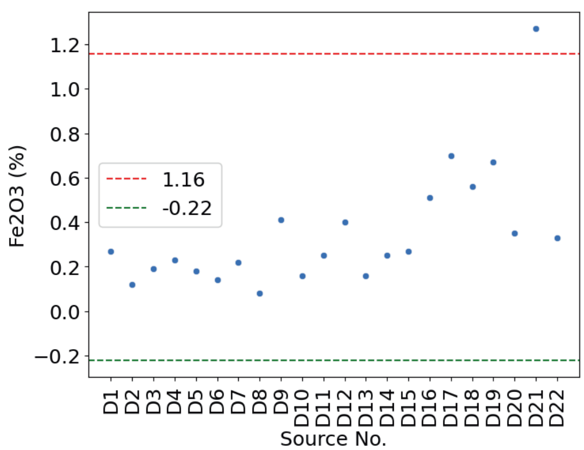
The findings indicate that D1 and D9 exhibit low minimum initial friction values and unstable friction performance, which may contribute to the reduced friction observed in certain pavement sections. Through the analysis of the relationships between



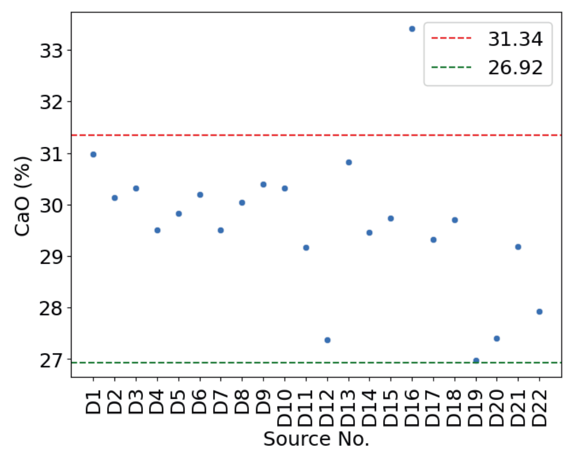
(a) Silicon Dioxide



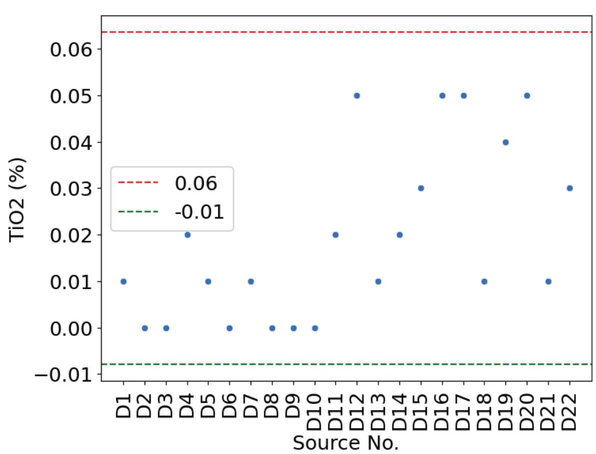
(b) Aluminum Oxide



(c) Iron Oxide

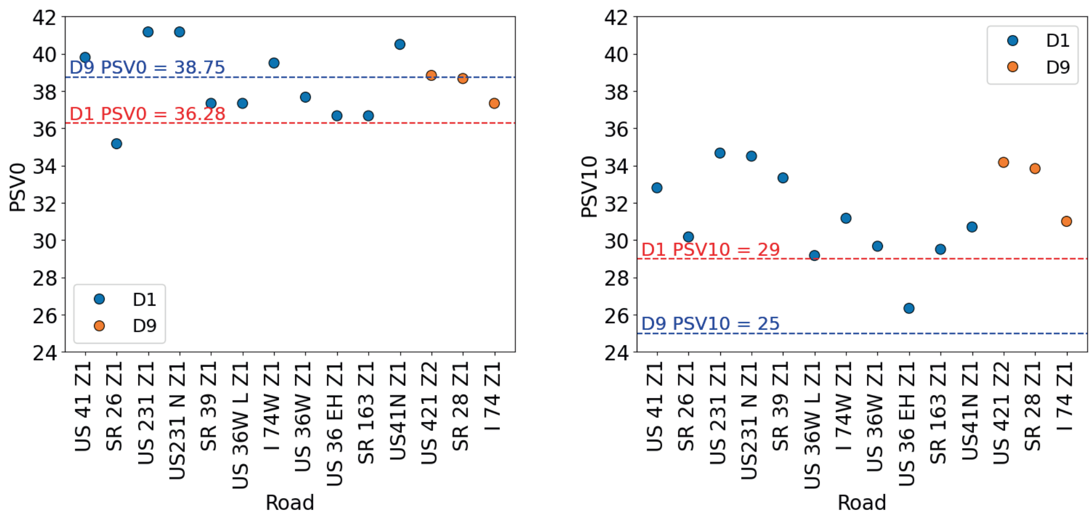


(d) Calcium Oxide



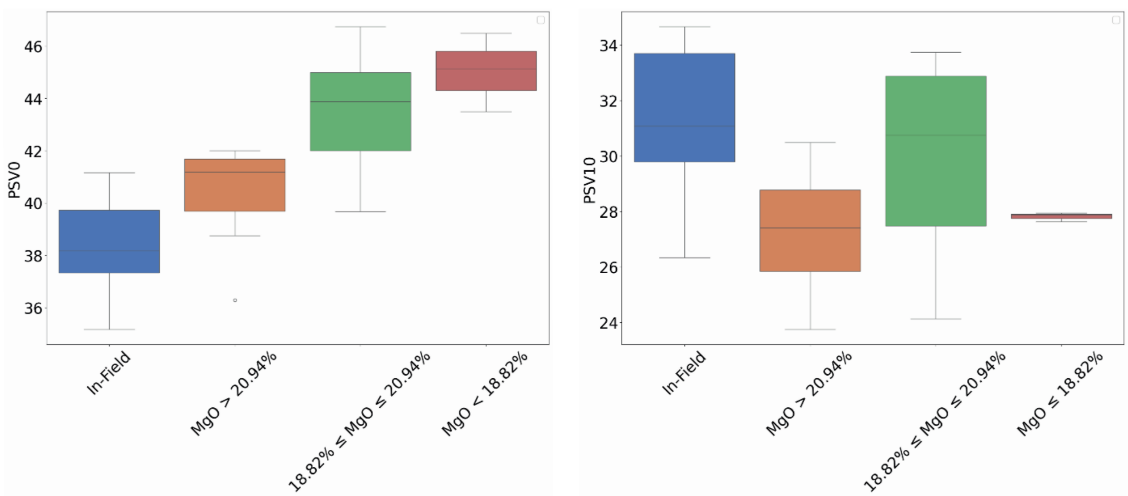
(e) Titanium Dioxide

Figure 3.32 Scatter Plot of Chemical Content Across Sources.



(a) PSV0 (b) PSV10

Figure 3.33 Scatter Plot of PSV0 and PSV10 of In-Field Collected Dolomites.



(a) PSV0 (b) PSV10

Figure 3.34 Boxplots of PSV Values for In-Field Aggregates and Laboratory-Tested Dolomites.

aggregate properties and friction performance, as well as interrelationships among the properties themselves, this study underscores the need to establish a magnesium threshold to ensure that PSV0 values meet the required performance standards for newly constructed pavements. Initial friction plays a crucial role in pavement safety, and inadequate PSV0 values can lead to premature friction deficiencies before significant polishing occurs.

Based on clustering analysis and field-collected data, the following recommendations are proposed:

- An optimal magnesium content range of 11.35% to 12.63% (corresponding to 18.82%–20.94% magnesium oxide) is recommended to achieve both sufficient initial friction and long-term durability.
- If additional aggregates are introduced to enhance abrasion resistance, limiting magnesium content below 12.63% may be necessary to maintain a balanced friction performance.

The following key implications for pavement friction performance should be noted:

- Field-collected aggregates exhibited PSV10 values that were generally comparable to or higher than laboratory-tested samples, suggesting that other aggregate components in the mixture contributed to friction retention.
- Lower PSV0 values indicate that the primary cause of low friction in these road segments is the inherently insufficient friction properties of the dolomite, rather than excessive wear over time.

- Traffic-induced wear (ΔPSV) was moderately correlated with AADT, confirming that high-traffic roadways are more susceptible to polishing effects.
- To achieve both sufficient initial friction and long-term friction retention, magnesium oxide content should be maintained within 18.82%–20.94% (magnesium: 11.35%–12.63%).
- If external aggregates (e.g., steel slag) improve abrasion resistance, limiting magnesium oxide below 20.94% may be necessary to optimize long-term performance.
- Additional field validation is needed to confirm the long-term effectiveness of mixed aggregate solutions in improving friction and pavement durability.

These findings provide a strong foundation for optimizing dolomite selection and pavement design strategies. By establishing an appropriate magnesium oxide threshold and exploring the role of secondary aggregates in wear resistance, pavement engineers can improve both the short-term and long-term friction performance of road surfaces. Although direct evidence is limited, the observed trend suggests that the presence of other aggregate types in the mixture may influence overall friction behavior. Further research and real-world validation are crucial for refining these recommendations to enhance roadway safety and durability. Future studies should investigate the interaction between dolomite and secondary aggregate components to optimize both initial friction and long-term friction retention in pavement applications.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Research Summary and Approach

Maintaining sufficient friction is essential for roadway safety, as it directly influences vehicle control, braking efficiency, and overall driving stability. In response to growing concerns over premature friction loss on newly resurfaced roads, the Crawfordsville District identified multiple pavement sections exhibiting unexpectedly low friction within a short time after resurfacing. Routine network-level and project-level friction testing confirmed that several resurfaced roadways had undergone significant reductions in friction, prompting a comprehensive investigation into material selection and pavement design practices.

An initial review of affected roadway sections revealed that dolomitic #11 crushed stone was the primary aggregate used in these pavements. However, standard laboratory evaluations of this dolomite source, including MDA, magnesium content, and macrotexture, indicated that its properties met existing specifications. Despite these findings, the observed decline in pavement friction suggested that additional factors were contributing to the issue. Given the critical role of friction in roadway safety, this study was designed to systematically examine the physical, mechanical, and chemical characteristics of dolomite aggregates and assess their influence on pavement friction performance.

The study employed a multi-faceted research approach, integrating laboratory testing, field data collection, advanced texture analysis, and statistical modeling. Laboratory evaluations included mechanical durability assessments such as LAA and MDA tests, while the chemical composition was analyzed through XRF techniques. Field testing measured friction and texture properties across various roadway sections, comparing results from different dolomite sources and mix designs. Additionally, hierarchical clustering and decision tree modeling were applied to determine optimal material thresholds, particularly magnesium oxide content, to balance initial friction (PSV0) and long-term friction retention (PSV10).

By combining laboratory findings with real-world performance data, this study provided a science-based framework for optimizing dolomite aggregate selection in HMA pavements. The insights gained from this research contribute to a deeper understanding of aggregate friction performance and offer practical recommendations for improving pavement material specifications to enhance roadway safety and durability.

4.2 Major Findings

4.2.1 Field Evaluation Findings

4.2.1.1 Pavement Friction Performance and Traffic Effects.

- A comparison of lateral friction measurements found that:
  - Wheel path locations (LWP & RWP) exhibited lower friction values than unpolished locations (shoulders and lane centers), confirming the impact of traffic-induced polishing.
  - Both microtexture and macrotexture are closely linked to aggregate friction properties and influence short-term friction loss and long-term friction retention in complex and subtle ways.

4.2.1.2 Influence of Aggregate Source and Mixture Design.

- Design properties in different DMF groups, including air voids and gradation, were not significantly related to the friction differences found in pavement sections that included #11 dolomite.
- Pavements using D9 dolomite exhibited significantly higher friction values compared to those using D1 dolomite ($p = 0.002 < 0.05$).
- Traffic exposure significantly affected macrotexture (MPD, RMS, and SV), with noticeable reductions in roughness over time.
- Mixture size (9.5 mm vs. 12.5 mm NMAS) did not show a statistically significant impact on wet friction performance at wheel path locations.
- The examined mixture NMAS sizes showed minimal impact on pavement friction and texture performance compared to the types of aggregate sources. Furthermore, transitioning from Superpave4 to Superpave5 does not have a significant effect on pavement friction performance in the first 0–5 years after construction.
- Higher truck traffic volumes (AADTT) were correlated with greater macrotexture deterioration, emphasizing the need for more durable aggregate selections for high-traffic roadways.

4.2.1.3 Relationship Between Texture Measurements and Friction.

- LTS, CTM, and DFT measurements provided complementary insights into pavement texture-friction relationships.
- Macrotexture parameters (MPD, RMS, and SV) correlated moderately with FN40 friction values, confirming the importance of texture roughness in maintaining friction.

- ANOVA tests indicated that microtexture RMS was significantly influenced by the dolomite sources (p = 0.0385), suggesting that aggregate composition plays a key role in determining friction.

4.2.2 Laboratory Evaluation Findings

4.2.2.1 Pavement Texture Evolution Under Simulated Traffic Wear.

- Macrotexture (MPD) remained relatively stable throughout the polishing cycles, indicating that surface roughness loss was not the primary factor contributing to friction deterioration. However, it is important to note that the laboratory simulation does not perfectly replicate field conditions. Lab-based polishing applies significantly lower loads than those exerted by truck tires in real traffic. In the field, vehicle tires may cause aggregate particle reorientation, potentially altering the macrotexture.
- Traffic volume (AADTT) was a significant factor in macrotexture roughness and friction performance, aligning with field observations.

4.2.2.2 Friction Performance Trends.

- DF40 values initially increased during early polishing cycles (up to 4,500 wheel passes) before gradually declining, reflecting the removal of asphalt coating followed by aggregate polishing.
- Final DF40 values (after 300,000 wheel passes) were the lowest recorded values, demonstrating the long-term impact of polishing on friction.
- Only two slabs retained DF40 ≥ 0.3 throughout the test, both from I-74W, which contained steel slag, a known high-friction aggregate.
- International Friction Index (IFI) parameters (F60 and S_p) confirmed that laboratory friction measurements aligned well with field friction data, validating the reliability of lab-based assessments.

Pavements using 9.5 mm NMAS mixtures exhibited higher friction values than 12.5 mm NMAS mixtures, supporting the hypothesis that larger aggregate sizes don't necessarily lead to better friction. It should be noted that the field evaluation yielded a different result: mixture size (9.5 mm vs. 12.5 mm NMAS) did not have a statistically significant impact on wet friction performance at wheel path locations. In the authors' opinion, the laboratory process may be better suited for compacting 9.5 mm NMAS mixtures in a way that more closely replicates field-like density and surface texture. This is because smaller aggregate sizes are generally easier to compact uniformly in the lab, allowing for better surface contact, fewer voids, and a more consistent texture that enhances friction performance. In contrast, field compaction involves variables such as pavement boundaries, equipment type, temperature variation, and traffic patterns, which may not always optimize the surface texture of 9.5 mm mixtures. This discrepancy can explain why lab results showed significantly better friction for 9.5 mm mixes, while field results did not show a statistically significant difference between 9.5 mm and 12.5 mm mixes.

4.2.2.3 Friction Performance of Dolomite Aggregates.

- The newly constructed pavement sections with low friction also exhibited insufficient initial friction (PSV0).
- While some dolomite aggregates had low initial friction (PSV0), their long-term friction retention (PSV10) was within acceptable limits.
- Field-collected aggregates exhibited PSV10 values comparable to or higher than laboratory-tested samples, due probably to the contribution of other types of aggregate in the mixture.
- Traffic-induced wear (ΔPSV) was moderately correlated with AADT (correlation coefficient = 0.51), indicating that high-traffic roadways are more susceptible to polishing effects.

4.2.2.4 Influence of Mechanical, Physical, and Chemical Properties.

- Mechanical properties (e.g., LAA and MDA) showed significant correlations with friction loss (ΔPSV), confirming that abrasion-resistant aggregates help maintain long-term friction performance.
- Physical properties, such as BSG and WA, demonstrated strong relationships with aggregate density and porosity, affecting both PSV0 and PSV10.
- Chemical composition played a critical role in friction behavior:
  - Magnesium content may play a critical role in friction performance. As magnesium content increases, abrasion resistance increases. However, a higher magnesium content may lead to low PSV0.
  - Dolomite aggregates with higher magnesium content tend to have better resistance to friction loss (ΔPSV), that is, better long-term friction under traffic applications.
  - Dolomite aggregates with high aluminum oxide and titanium dioxide are likely have greater resistance to polishing.

4.2.2.5 Establishing a Magnesium Oxide Threshold for Optimal Friction Performance.

- Clustering analysis identified an optimal magnesium oxide content range of 18.82–20.94% (magnesium: 11.35–12.63%) to ensure both sufficient initial friction and long-term durability.
- Dolomite aggregates with magnesium oxide content below 18.82% had higher initial friction but suffered greater polishing loss (higher ΔPSV), making them less suitable for long-term pavement performance.
- Dolomites with magnesium oxide content exceeding 20.94% exhibited lower PSV0 values, potentially leading to early-stage friction deficiencies.
- Dolomite aggregates with magnesium oxide content below 18.82% are likely to have higher initial friction but lower polishing resistance (higher ΔPSV). Nevertheless, dolomites with magnesium oxide content exceeding 20.94% are likely to have lower PSV0 values, potentially leading to early-stage friction deficiencies.
- The presence of secondary aggregates (e.g., steel slag) in the mixture improved abrasion resistance, highlighting the need for further research on the combined effects of different aggregate types.

4.3 Recommendations

This research provides a comprehensive, data-driven approach to improving aggregate selection and pavement design to optimize friction. The identification of an optimal magnesium oxide content range (18.82–20.94%) provides a valuable guideline for transportation agencies, pavement engineers, and material suppliers seeking to enhance pavement safety and durability.

4.3.1 Refinement of Aggregate Selection Criteria

- The vast majority of dolomite samples from different sources contained more than 10.3% magnesium, indicating that the current INDOT minimum magnesium content of 10.3% for dolomite is well justified.
- The friction properties of dolomite aggregate vary with their magnesium content. The test results suggest that dolomite aggregates with magnesium content of 11.35–12.63% (magnesium oxide: 18.82–20.94%) can minimize early-stage friction deficiencies while maintaining long-term friction performance.
- To enhance the early-stage friction performance of pavements using dolomite aggregates, it is necessary to ensure necessary aggregate angularity and sufficient crushed particles. It is also shown that blending dolomite aggregate with steel slag is an effective approach to enhance friction performance.
- Macrotexture and microtexture parameters should be jointly considered when evaluating pavement friction.
- Close-range photogrammetric methods could enhance texture analysis accuracy, particularly for assessing PSV test specimens in laboratory settings.
- The use of IFI parameters (F60 and S_p) in pavement friction assessments should be expanded, as they demonstrated strong correlations between field and laboratory results.
- Develop guidelines for the inclusion of secondary aggregates (e.g., steel slags and calcined bauxite) to improve abrasion resistance and enhance long-term friction.

4.3.2 Further Research and Field Validation

- Further validation is necessary to refine the recommended magnesium thresholds and assess their effectiveness across different pavement conditions and traffic volumes.
- Future research should also investigate the interaction between dolomite and secondary aggregate components to optimize mixture designs for enhanced friction performance.
- Further investigation is needed into the long-term effects of mixture size variations on friction performance, as laboratory results differed from field observations.

4.3.3 Practical Implementation for Roadway Safety

- Integrate the findings into pavement design strategies to improve roadway safety and durability.
- Establish performance monitoring programs to assess the long-term effectiveness of dolomite aggregates in different environmental and traffic conditions.

4.3.4 Potential Benefits and Applications

- Improved roadway safety: Optimizing dolomite selection will reduce accident risks caused by low-friction pavement surfaces.
- Enhanced pavement longevity: Selecting the right magnesium oxide range will improve resistance to polishing, reducing maintenance and resurfacing costs.
- Cost-effectiveness: Implementing a magnesium oxide-based selection criterion can minimize unnecessary repaving and friction restoration projects, leading to long-term cost savings for transportation agencies.

This study systematically examined the relationship between HMA mixture designs, dolomite aggregate sources, and pavement texture properties through extensive field and laboratory evaluations. Key findings indicate that aggregate type plays a dominant role in determining microtexture characteristics and friction performance, while mixture size influences short-term friction. Field and laboratory results consistently highlighted the importance of selecting aggregates with superior microtexture retention for maintaining long-term pavement friction. Implementing the insights from this study is expected to enhance roadway safety, extend pavement durability, and optimize friction management strategies for long-term performance.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at docs.lib.purdue.edu/jtrp/.

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